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# The shear strength of A325 and alloy steel structural bolts

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# THE SHEAR STRENGTH OF A325 AND ALLOY STEEL STRUCTURAL BOLTS

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TABLE OF CONTENTS

## ABSTRACT

In many bolted connections, the fasteners are subjected to a shear loading. The objective of this study was to determine the performance and behavior of single, high-strength bolts under static shear loadings.

A total of 81 bolts were tested in jigs made of A440 and constructional alloy steel. The bolts used were A325, A354 BC and A354 BD (or A490) bolts.

The effect of a number of variables upon the ultimate shear strength and deformation at ultimate load was studied. The variables were internal bolt tension, bolt grade and diameter, connected material, grip and loading span, end restraint in the tension jigs and type of testing device. The only variables which significantly affected the ultimate shear strength were the grade of bolt and the type of testing device.

# 1. INTRODUCTION

When evaluating the behavior and performance of a bolted or riveted structural connection, it is necessary to first determine the behavior and performance of the component parts. The static strength of the connected material is determined by coupon tests of plate material that has originated from the same ingot and rolling as the connected material. If joint failure occurs at the net section through the holes, the joint strength can then be compared to the ultimate strength of the tensile coupon. This comparison will yield the "net efficiency" of the joint.

The other component of the structural connection is the fastener or the connecting medium. Under applied loads, the fasteners in a butt-type splice joint are subjected mainly to a shearing force. A means of determining the shear strength and behavior of individual fasteners is desirable in order that the performance of single fasteners may be compared to that of fasteners in a large connection.

Within the last 100 years, the three most prominent methods of connecting structural components have been welding, riveting and bolting. In this paper, welding will not be discussed. Of the three, probably the oldest means of fastening has been use of the hot-driven rivet. In past years, much research has been conducted on the behavior of riveted components. This continued to be the main method of fastening structural elements until 1951, when the Research Council on Riveted and

Bolted Structural Joints approved the "Specification for Assembly of Structural Joints Using High-Strength Steel Bolts"(1). When compared to rivets, the advent of the high-strength A325 bolt meant quieter, faster and more economical steel erection. Eventually, there was also a reduction in the number of fasteners needed to resist a given load. Figure 1 depicts the results of double shear tests conducted on the A141 rivet, the high-strength A325 bolt and the new higher strength A490 bolt. The ordinate in Fig. 1 is shear stress on the fastener, while the abcissa is the deformation of the fastener under applied load. Test points have not been shown, since the figure is used mainly for comparative purposes. This figure shows that the A490 bolt has a higher load-carrying capacity than the A325 bolt. Both can carry more load than the hot-driven rivet. However, there is a small decrease in ductility as the strength of the fastener increases.

Many higher strength steels are now readily available, for instance, A242, A440, A441 and constructional alloy steel. In order to develop the strength of these steels so that they may used economically and effectively, a higher strength fastener was desirable. The A354 BC and A354 BD high-strength bolts have been in existence for some time, although their use was not dictated by the higher strength steels alone and they have not been used, to any great extent, for ordinary structural application.

The greater proof load and ultimate tensile strength of the A354 BD and A490 bolts offer greater resistance to slip as well as increased shear and tensile strength when compared to the A325 bolt. This higher bolt strength means that better-proportioned connections will result when high strength steel joints are subjected to large forces. A research program was initiated to study the basic tensile and shear properties of the A354 BC, A354 BD and A490 bolts. The behavior of these bolts in direct tension, torqued tension and their response to other special tests can be found in Refs. 2 and 3. Results of similar tests conducted on the A325 bolt can be found in Ref. 4.

## 1.1 PURPOSE AND OBJECTIVE

The main objective of the study as reported herein was to determine the double shear strength of single A354 BC and A354 BD or A490 bolts and to investigate the effect of a number of variables on the ultimate shear strength and the deformation at ultimate load. In addition, it was desirable to establish complete load-deformation relationship of the fasteners. With this information, the analysis of the load-deformation behavior of large joints could be determined, since their performance depends not only on the strength of the fastener but also on its deformation capacity.

Shear tests of single A325 bolts were summarized in Refs. 5, 6 and 7. Additional test results and details not readily available in these papers will be incorporated into this report.

An analysis of the test data was conducted to see if certain variable parameters which describe the behavior of a single bolt subjected to shearing forces could be related to the mechanical properties of the bolt and the steel it connects. In this phase of the investigation, Lehigh University's GE 225 high speed digital computer was used.

The test series included in this report represents one phase in the study of the ultimate strength of bolted joints. The interpretations and conclusions reported herein are based on the results of double shear tests of single 7/8 in. and 1 in. diameter fasteners tested in A440 and constructional alloy steel testing jigs.

## 1.2 HISTORICAL BACKGROUND

A considerable amount of experimental and theoretical work has been conducted on bolted and riveted joints. In general, most of these tests were on small scale specimens; only a few large tests have been conducted. Although many of the studies were concerned with joint strength, the single and double shear behavior of single bolts was investigated.

C. Batho[8], in 1931, used various grades of single black bolts installed in single and double shear tension jigs to determine the relationship between the installed torque and the slip load. The tension jigs that were used in this investigation were very similar to the ones in the study as reported herein. However, only one of the bolts was tested to failure. Load and deformation readings were taken up to slip load for all tests.

Wilson and Thomas[9], in conjunction with fatigue tests, conducted static tests on the behavior of 1 in. rivets loaded in double shear. The number of fasteners in the joint varied from two to eight. Also in conjunction with fatigue tests, Baron and Larson[10] showed that the substitution of high-strength A325 bolts for rivets does not change the plate efficiencies of a joint subjected to static load.

Munse, Wright and Newmark[11], in an extensive test series, used 3/4 in. A325 bolts to determine the static and fatigue behavior of bolted joints. They found that the initial bolt tension had little effect on the ultimate shear strength. Also, tests of two-bolt and three-bolt lap joints and two-bolt butt joints indicated that the type of joint had little effect on the ultimate shear strength. For the two-bolt butt type joints in which bolt failure occurred, the ultimate shear stress was found to be about 77 ksi.

Tests conducted on large bolted joints at Fritz Laboratory included material calibration[6][12]. Tests to determine the basic shear strength of single A325 bolts were conducted by placing a bolt in a loading jig that produced double shear. Bolts were installed in jigs with lubricated and non-lubricated faying surfaces, and were torqued to various degrees of tightness. Bolts in the non-lubricated jigs failed at slightly higher loads, indicating that friction carried a small but negligible portion of the ultimate load. Also, internal tension had no effect upon the ultimate shear stress. The average ultimate shear stress for 7/8 in. and 1 in. A325 bolts was 80 ksi., and 84 ksi for 1-1/8 in. bolts.

Recent tests at the University of Illinois[13] have shown that the effect of using different joint materials had a negligible influence on the single shear strength of A325 and A354 BD bolts. Also, it was found that, in direct shear, the A354 BD bolts were about 25% stronger than the A325 low hardness bolt and 5% stronger than the A325 high hardness bolt.

# 2. THE EXPERIMENTAL STUDY OF A325 AND ALLOY STEEL BOLTS

## 2.1 BOLT MATERIAL PROPERTIES AND BOLT DESCRIPTION

The A325 bolts that were used in the experimental program were manufactured from quenched and tempered medium carbon steel in accordance with ASTM A325[14]. Similarly, the A354 and A490 bolts were manufactured from quenched and tempered alloy steel in accordance with ASTM A354[15] and ASTM A490[16], respectively. All bolts were purposely ordered near the minimum tensile strength as called for in the appropriate specification, in order to help establish the minimum shear strength. A number of A354 bolt lots used for this study were of a special manufacture. The heavy-head bolts were made to conform to the size requirements as specified in ASTM A325 by reheat-treating AISI 4140 alloy steel bolts that had been obtained from a Canadian firm. As a result of this reheat-treating, variation in the physical properties existed between the various lots of bolts.

A complete description of the direct tension and torqued tension properties of the A354 and A490 bolts can be found in Ref. 3, while Ref. 4 contains the direct tension and torqued tension tests results of the A325 bolts.

The A325, A354 and A490 bolt shanks were measured with a 1 in. micrometer to see whether the actual bolt diameter varied greatly from the nominal diameter. It was found that the 7/8 in. diameter bolts were undersized by a maximum of 0.003 in. whereas the 1 in. diameter bolts were undersized by a maximum of 0.005 in. Thus, the maximum difference in ultimate bolt shear stress computed on the basis of the actual and nominal bolt diameter was about 1 ksi for 1 in. bolts. This value was less than 1 ksi for 7/8 in. bolts. Because of the small difference, the nominal diameters were used to compute all shear stresses.

The chemical properties of the different bolt grades that are controlled by the appropriate specification are given in Table 1. This table shows that the A354 and A490 specifications contain no control over the carbon content as these are alloy steel bolts.

In order to determine the mechanical properties of the bolt parent material, 0.505 in. diameter tensile specimens were machined from the full-sized A325, A354 and A490 bolts. Figure 2 shows a photograph of a typical specimen before and after testing. The complete load-deformation data was recorded and was then converted to stresses and strains. The deformations in the elastic and initial inelastic range were measured with a Peters' gage, while in the plastic and strain hardening range a pair of dividers and steel scale was used. The initial gage length was about 2 in. Figure 2 also shows a typical stress-strain curve for an ED lot, A354 BD 0.505 in. coupon. For these coupons there is not, in general, a distinct yield plateau such as that exhibited by low alloy, low carbon steels such as A7, A36 or A440.

Table 2 is a summary of the 0.505 in. tensile coupon test results. In this table, the full-size bolt tensile strengths are compared to the 0.505 in. tensile strengths. The former were found to be greater, in all cases, than the latter. This result occurs partly because the notch-effect of the bolt threads restrains necking in the bolt and a higher ultimate tensile strength can be obtained. Also, the full-size tests take into account variations in material strength due to the quench and tempering process, whereas the 0.505 in. specimens were machined from the centerline of the bolt. This difference in strength between the full-sized bolts and 0.505 in. specimens was greatest for the larger diameter bolts, lots DC and FD. The difference in strengths is greater for the 1" FD lot, A354 BD grade than for the 1" DC lot, A354 BC grade. This difference is probably due to the different methods of heat-treating the BC and BD grade bolts.

Table 3 describes the various lots of bolts that were used in this investigation. Two grades of A354 bolts, BC and BD, together with A325 and A490 bolts were included in this study. One type of bolt conformed to the requirements for regular semi-finished bolts as specified in ASA B18.2 (17) and called for in the ASTM A354 (15) specification. The second type of bolt was similar to the heavy hexagon structural bolt manufactured in accordance with ASTM specifications A325 (14) and A490 (16). The heavy head bolt had a shorter thread length than the regular head bolt.

Both ends of each bolt were stamped with a lot designation and number. The bolts were centerdrilled to accommodate the C-frame extensometer, which was used to measure the changes in length due to tightening.

Three lots of A354 BC bolts were used: lots AC, CC and DC. AC lot bolts had heavy heads while CC and DC lots both had regular heads.

Three lots of A354 BD bolts were used: lots ED, FD and GD, all of which had regular heads. A490 bolt lots KK and JJ were originally not part of this investigation but the test results are included in this report for completeness. Several special shear tests of A325 bolts, which were conducted in previous years at Fritz Laboratory, are also reported.

## 2.2 PLATE MATERIAL PROPERTIES

In order that the effect of the connected material on the ultimate shear strength of the bolt could be evaluated, the plates used in the test jigs were made of two different steels: a) A440 steel and b) constructional alloy steel, hereafter referred to as "Q & T" steel. The plate mechanical properties are summarized in Table 4.

The A440 tensile coupons were cut from the same plate material that was used to manufacture the A440 shear jigs. These coupons were 1 in. thick and were machined to 1.50 inches in width. The gage length used for measuring strains was 8 in. In all, forty A440 tensile coupons were tested. The Q & T coupons were also 1 in. thick and were machined to 1.50 in. in width. Six Q & T specimens were tested. Details of the test procedures and results are given in Ref. 6.

Table 4 shows that the Q & T steel is stronger but less ductile than the A440 steel.

## 2.3 DESCRIPTION OF TEST JIGS

In order to determine the double shear strength of the single bolts, two types of shear-inducing devices were used, as shown in Figs. 3a and 3b. The shear devices will be referred to hereafter as bolt test jigs. Double shear bolt test jigs were used, since they provide load symmetry and since the large bolted joints tested in Fritz Laboratory were usually double shear connections.

Both test jigs were subjected to axial loading. The plates of the compression jigs (Fig. 3a) were subjected to a compressive load, whereas axial tensile loads were applied to the plates of the tension jigs (Fig. 3b).

The 4 in. compression test jig shown in Fig. 3a, was composed of two 1 in. lap plates connected to two 1 in. main plates by a single test bolt. The 4 in. tension jig, shown in Fig. 3b, was similar to a butt-type joint with two 1 in. lap plates and two 1 in. main plates. In the tension jig, three bolts were used to connect the plate material so that only one bolt, the test bolt, was critical. As is usual practice, the bolt holes in the plates of both test jigs were 1/16 in. larger than the nominal bolt diameter.

For grips exceeding 4 inches, additional plies of 1 in. material were used to provide the desired grip lengths. For the 8 in. grip test jigs, the lap plates consisted of two 1 in. plies each, and the main plate member was composed of four 1 in. plies to provide equal lap and main plate bearing area. In addition, this arrangement insured a constant loading span-grip ratio of ½, where the loading span is defined as the thickness of the main plate (2 in. or 4 in.) and the grip is defined as the distance from the underside of the bolt head to the face of the nut when the bolt is installed in a test jig. All plies were arranged symmetrically with respect to the bolt jig centerline. Small changes in the total grip length were accomplished by placing extra washers under the bolt head. This did not affect the bolt bearing area.

The bolt jigs were designed to have the same plate thickness (1 in.) as full size joints that have been tested at Fritz Laboratory. The width of the jigs was large enough so that the axial strains were minimized. The bearing and bending conditions of the bolts in the test jigs were comparable with similar conditions in the larger joint tests.

Other investigators have used hardened steel inserts to test bolts in single shear[13]. These bolts were then installed in a testing fixture which could apply a shear force, a tensile force or a combination of the two as a load on the bolt. In these tests, only the ultimate strengths of the bolts were reported.

## 2.4 BOLTING UP PROCEDURE

The bolt jigs were assembled with the test bolts in bearing in order to minimize slip as much as possible. A smooth curve describing the load-deformation relationship is needed to help determine the load partition in bolted bearing-type connections. Therefore, it was desirable to eliminate the joint slip from the observation. All faying surfaces were clean mill scale, and the steel was used in its as-received condition. Figure 4 shows a compression jig in the bolting up fixture. The attached C-frame, used to measure the bolt elongation, is shown attached to the bolt to be tested. The outer plate with two fasteners serves to hold the test jig in the slipped position during tightening. Because of the size and configuration of the tension jigs, it was not convenient to remove the slip when bolting up. However, the slip was removed by preloading the tension test jig in the hydraulic testing machine as described in Art. 2.6.

Bolts from each lot were calibrated[2][18] in torqued tension to determine the internal bolt tension-elongation relationship. The bolt preload could then be determined by measuring the bolt elongations and relating these elongations to the proper calibration curve. All bolts were installed in the tension and compression jigs to an elongation which corresponded to at least proof load, except for those bolts in which preload was the major variable. No attempt was made to tighten the bolts to the same elongation. As will be shown in Section 3.3, the initial bolt preload had little, if any, effect upon the ultimate shear strength of the bolt.

The initial bolt tension was induced by turning the nut against the connected material, using a hand torque wrench. The changes in the bolt length could be conveniently measured with the Ames dial extensometer when the jig was held by the bolting up fixture.

## 2.5 BOLT JIG INSTRUMENTATION

The instrumentation of a typical tension jig is shown in Fig. 5. Two 0.0001 in. Ames dial gages were attached to the main plates at the centerline of the bolt hole. The plungers of the dial gages rested on yokes which were tacked-welded to the lap plates at the initial level of the dial gage support. This instrumentation enabled the relative movement of the centerlines of the bolts due to shear and bending to be measured. Also included in the measurement was the deformation of the holes due to bearing stresses.

The deformation of the compression jigs was measured by placing one 0.0001 in. dial gage between the fixed and moving heads of the testing machine as shown in Fig. 6. The deformation measurement thus included the relative movement of the bolt due to shear and bending, the bearing deformation in the lap and main plates, the axial shortening of the plates, and the deformation within the testing machine itself.

To determine the order of magnitude of the deformations within the testing machine and other portions of the test assembly and to determine what influence these had on the compression test jig deformation readings, one compression jig was conducted with the dial gages mounted on the test jig in a manner similar to that of a tension jig. The bolt used was an A354 BC bolt, DC lot. Figure 7 shows the load-deformation curves for the DC lot bolts tested in the two types of compression jigs. It can be seen that the deformation at ultimate load is less for the bolt tested in the special compression jig than for the bolt tested in the normal compression jig. Further test results are discussed in Section 3.2.

## 2.6 TEST PROCEDURE

The initial test procedure was the following. After the test specimen was gripped in the testing machine, the jig was loaded continuously until failure. However, in both the tension and compression jig, slip was observed to occur, thus indicating that the assembly process was not altogether successful. As a result, it was necessary to modify the testing procedure somewhat.

The modified testing procedure consisted of first loading the bolt jigs until major slip occurred. For 7/8 in. dia. bolts this load was approximately 30 kips while for 1 in. dia. bolts, this load was approximately 60 kips. The load was then removed and the actual testing of the bolt commenced.

The tension jig tests were conducted in a 300 kip Universal hydraulic testing machine (Fig. 5). After gripping the test jig and removing the residual slip, the specimen was loaded continuously until failure occurred. Load and deformation readings were recorded at 10 kip intervals until the difference in deformation readings was 0.01 inches. Thereafter, a deformation criteria was used to control the test, and load readings were taken at 0.02 in. intervals. On most of the tension specimens, the Ames dials were not removed from the test jigs after ultimate load had been reached.

The compression jig tests were also conducted in the hydraulic testing machine. The test jig was placed in the center of the testing heads with the bolt perpendicular to a line between the loading screws.

The movable head was lowered until it was in contact with the test jig. The dial gage was then placed between the heads and initial readings were taken. Load and deformation readings were recorded at 10 kip intervals until a deformation criterion of 0.02 in. controlled the load readings. The load was applied such that the cross head was 0.01 in./min. in the elastic range and 0.02 in./min. in the inelastic plastic range.

Several tests of A325 bolts installed in tension test jigs indicated that the loading speed had little if any effect on the load-deformation curve. As the A325 bolt approached its ultimate shear load, the loading valve on the testing machine was closed and the load was allowed to stabilize. In most cases, this took only a few minutes. It was found that the load dropped only 1 kip in 100 kips. Thus, the difference between static and dynamic shear loading readings was assumed to be negligible. All plotted points in the figures are dynamic readings.

## 2.7 THE EXPERIMENTAL PROGRAM

The experimental program was formulated to measure the effect of certain variables on the ultimate shear strength of the bolts and their deformation at ultimate load. The testing program that was set up to determine the effect of these variables is mainly an outgrowth of research that has been conducted on rivets(19)(20), as well as the observed behavior of tests on large bolted connections(7)(21).

The variables included in this investigation were the following:

(1) Type of testing device (tension jig or compression jig)

(2) Initial bolt preload

(3) Bolt grade

(4) Bolt diameter

(5) Type of connected material

(6) Grip and loading span

(7) End restraint in the tension jig

Tests of A325 bolts have shown that the type of testing jig influenced the complete load-deformation curve[(6)]. Ultimate shear strengths were found to be about 10% higher for a bolt tested in a compression jig than for a bolt tested in a tension jig. It would be desirable to know in what manner this variable influenced the behavior of A354 BC and A354 BD bolts.

It has been generally believed that upon yielding, the effect of the rivet clamping force was removed and the ultimate shear strength of the rivets was not affected by the variation in rivet clamping force. The question has been raised: "When we install a bolt by torquing, does this reduce its ultimate shear strength?" or "What happens when we torque a bolt to near-failure - is its ultimate shear strength reduced?" This paper provides an answer to these questions.

It was obvious that the A490 and A354 BD bolt was stronger than the A354 BC bolt, which, in turn, was stronger than the A325 bolt. However, it was of some practical interest to see just how much more shear load-carrying capacity one bolt grade had over another.

Research on rivets has shown[19] that a variation of diameter had no large or consistent effect upon the ultimate shear strength of a rivet. The effect of diameter on the shear strength of bolts was questioned. Also, since the use of high strength bolts (or rivets, for that matter) is not restricted to connecting one type of steel, it was desirable to see what effect different steels had on the bolt behavior and performance.

Research on rivets has shown that, in general, the ultimate strength decreased about 10% with an increase in grip length from 1 to 5 inches. The lower strengths were attributable to the fact that the longer rivets did not fill the holes as well as the shorter rivets, and the longer rivets had different strength properties than the shorter rivets because of the difference in working the material during driving. Thus, it was questioned if bolt shear strength would decrease with an increase in grip.

It was desirable to know the answer to the question - if the lap plate prying action (to be explained later) in a tension jig is minimized, will the ultimate shear strength of a bolt approach that of a bolt tested in a compression jig? An affirmative answer to this question would justify, to some extent, the use of the compression jig as a testing device. In a joint containing several fasteners, the lap plates are restrained from bending freely between the interior fasteners. Hence, it was desirable to determine what effect the restraint of the free ends would have on the ultimate strength and deformation of single bolt joints. Similar studies have been conducted on riveted aluminum joints[22].

Table 5 describes the bolt lots used in the study, together with the number of bolts tested in the A440 and constructional alloy steel tension and compression jigs. The reported grip included the nominal grip of 4 or 8 inches plus one or two 1/8 in. hardened washers.

In all tests, the shearing plane passed through the full shank area and not through the thread or thread runout. For bolt lots DC and FD, this requirement necessitated machining 0.16 in. and 0.20 in., respectively, off of the underside of the bolt head so that the shear planes did not pass through the threads. As far as could be ascertained, this had no adverse effect upon the bolt behavior. In all, 36 A354 bolts were tested in the tension jigs and 39 bolts were tested in the compression jig.

# 3. TEST RESULTS AND ANALYSIS

## 3.1 INTRODUCTION

The double shear test results of the individual bolts are given in Tables 6 and 7 for the compression jig and tension jig tests, respectively. The ultimate strength and fracture load values are given in kips while the deformations are reported in inches. Average load and deformation values are then computed at ultimate and fracture loads. The bolt grades include A325, A354 BC, A354 BD and A490 high strength bolts.

The shear test results are summarized in Table 8 for the compression and tension jigs. Mean values of the shear strength and the deformation at ultimate load of bolts tested in A440 and Q & T steel jigs are given. The ultimate shear stress was obtained by dividing the ultimate load by twice the nominal shank area, since both shear planes passed through the shank.

The bolt tensile strengths as given in Table 9 are based on the ultimate tensile load obtained from direct tension tests[2]. The tensile stress area is defined in the footnotes in Table 9, and is an attempt to include the effect of the threads upon the tensile strengths. The bolt tensile strengths were used to compute the minimum shear strengths, which are given in Table 9 for bolts tested in A440 and Q & T steel jigs. These minimum shear strengths were computed on the basis of the formula:

$$\tau_{min} = \frac{\sigma_{min}}{\sigma_{act}} \times \tau_{act} \qquad (1)$$

where $\sigma_{min}$ is the minimum bolt tensile strength as specified in ASTM

A325, A354, and A490. The actual bolt tensile strengths, $\sigma_{act}$, are given in Table 9 and were computed on the basis of the tensile test results on full-size bolts[2]. A more conservative value of the minimum shear strength will result if the bolt tensile strengths are based upon the full-sized bolt tests, rather than the 0.505 in. coupon tensile tests. The ultimate shear strength, $\tau_{act}$, is the double shear strength of a single fastener in either a tension or a compression jig.

The following average minimum shear strengths were obtained for the three types of bolts tested and they were computed without regard to the type of connected material, since it had no effect upon the ultimate shear strength. As would be expected, the tension jig test results gave the lowest values of the minimum shear strength. Thus, the minimum shear strength for A325, A354 BC and A354 BD (or A490) bolts tested in tension jigs was 76.7 ksi, 78.7 ksi, and 91.9 ksi respectively. For the same bolt grades tested in compression jigs, the minimum shear strengths were 86.5 ksi, 86.8 ksi and 102.8 ksi respectively.

The deformation of the fasteners as reported in Table 7 for the tension jigs included the effects of shearing, bending and bearing deformation of the bolts as well as the localized bearing deformation of the main and lap plates. For the compression jigs, the deformation measurement included, in addition to the aforementioned deformations, axial deformation of the test jig and deformation within the testing machine. However, for the range of loads encountered, the axial test jig deformation was small.

Figure 8 shows a deformed bolt which illustrates the shear, bending and bearing deformations. This figure shows that the plate bearing deformations were greater near the shear plane. Figure 9 illustrates an A325 bolt at various stages of loading. The stress-deformation curve shows the points at which loading of the compression jig was stopped and the jig then sawed in half. The first three stages showed little visual deformation. However, stages 4, 5 and 6 show an increasing amount of shear, bending and bearing deformation, as can be seen from the photographs in Fig. 9.

As was expected, the type of bolt head (regular or heavy) had no appreciable effect on the shear strength or behavior of single bolts in double shear.

## 3.2 EFFECT OF TESTING DEVICE

The influence of the type of testing device on the ultimate shear strength and deformation of ultimate load is illustrated in Fig. 10 where typical mean stress-deformation curves compare the shear behavior of the DC lot bolts installed in a tension jig with the shear behavior of the same lot of bolts installed in the compression jig. The mean stress-deformation curves shown in Fig. 10 are based on all the test data for all bolts from the same lot and test conditions. Subsequent figures are plotted in the same manner. This then provides a visual idea as to the variation between the individual tests. Both Fig. 10 and summary Table 8 show that the ultimate shear strength of bolts tested in a tension jig is lower than when the bolt is tested in a compression jig.

When considering all of the test results, the ultimate shear strength for bolts tested in the tension jigs is 6% to 13% lower when compared to the compression jig tests using A440 steel. This same trend was observed in the Q & T jig tests with the percent reduction in strength varying from 8% to 13%. In general, the deformations at ultimate load can not be compared, because of the two different deformation measuring systems used. However, one DC lot bolt was tested in a compression jig which was instrumented in the same manner as the tension jig. The deformation at ultimate load for this bolt was 0.224 in. almost identical to that of DC lot bolts tested in a tension jig. Thus, the deformation within the testing machine itself due to compressive forces is appreciable.

The reduction in shear strength when a bolt is tested in a tension jig is due to lap plate prying action, a phenomena which tends to bend the lap plates of the tension jig outward. The lap plate prying mechanism is shown in Fig. 11. Referring to this figure, due to the uneven bearing deformations of the test bolt, the resisting force P/2 does not act at the centerline of the lap plate, but acts at a distance "e" to the left of it. This sets up a clockwise moment $M_L = P/2(e)$, which tends to bend the lap plate away from the main plate. However, this moment, $M_L$, is resisted by the counterclockwise moment $M_R = \Delta T(a)$. This is the moment which induces an additional tensile force, $\Delta T$, into the bolt.

Catenary action may also contribute to the increase in bolt tension near ultimate load. However, it is believed that this effect is small when compared to the tension induced by lap plate prying[27]. In any case, the catenary effect is present in both the tension and compression jig tests.

If, for illustration sake, Mises' Yield Criterion is extended to ultimate conditions, it can be shown that:

$$\sigma_u^2 = \sigma_t^2 + k\tau_u^2 \tag{2}$$

where $\sigma_u$ = ultimate tensile strength of the bolt

$\sigma_t$ = tensile stress component

$\tau_u$ = shear stress component at ultimate load

$k$ = a constant

This equation must always be satisfied and it follows that if $\sigma_t$ increases due to $\Delta T$, the ultimate shear stress, $\tau_u$, must necessarily decrease, since $\sigma_u$ is a constant for a given bolt lot. Hence the decrease in shear strength for bolts tested in tension jigs is to be expected.

Other tests of large bolted joints have shown that the bolt under the highest combined tension and shear stress will be the first bolt in the joint to fail[27]. Also, the lap plate prying action is visually evident in these large joint tests as can be seen in Fig. 12. Tests reported in Ref. 13 of bolts under combined tension and shear have indicated that the tensile component does reduce the ultimate shear strength of the fastener.

## 3.3 EFFECT OF INITIAL BOLT PRELOAD

The effect of initial bolt preload on the ultimate shear strength is illustrated in Figs. 13 and 14 for A325 and A490 bolts respectively. All shear jig specimens had a 4 in. grip and both shearing planes passed through the bolt shank. The preloads were induced by turning the nut against the resistance of the gripped material. The faying surfaces were clean mill scale and all bolts were from the same lot.

Two different grades of bolts were tested. Lot 8B was an A325 bolt with a heavy head and a short thread length. The A490 bolts (lot KK) had dimensions similar to the 8B lot bolts.

The A325 bolts were elongated to either a "snug" preload (about 8 kips), ½ turn-of-nut, or 1½ turn-of-nut. The A490 bolts (see Fig. 14) were tested at "snug" preload, ½ turn-of-nut and 1 turn-of-nut. The torqued tension calibration curves for the 8B and KK lot bolts are given in the upper portion of Figs. 13 and 14 respectively. These curves were established by torquing bolts in the Skidmore-Wilhelm bolt calibrator with 1/8 in. thread in the grip. Both the bolt tension and bolt elongation were measured as described in Ref. 2. The lower portion of Figs. 13 and 14 shows the variation of ultimate bolt shear strength with varying amounts of initially induced preload, as determined from measured bolt elongations.

The figures illustrate that there is no consistent variation of the ultimate shear strength with varying amounts of initial bolt preload. The variation in the individual bolt shear strengths was almost equal to the variation in shear strengths for the different magnitudes of induced preload.

A number of reasons may be advanced to explain the above phenomena. When a bolt is torqued to a certain preload, most of the inelastic deformations develop in the threaded portion of the bolt, and not in the shank. Thus, one would expect very little influence of the internal bolt tension on the ultimate shear strength, since all failure planes were through the bolt shank.

Also, measurements of the internal tension in bolts installed in large joints have indicated[27] that at ultimate load, there is little initial clamping force remaining in the bolt. Hence, the initial preload had little, if any, effect on the ultimate shear strength, since, at ultimate load, there is little bolt tension present. Any tension introduced into the bolt due to prying action would occur regardless of the initial tension.

3.4 <u>EFFECT OF BOLT GRADE</u>

The effect of bolt grade is illustrated by comparing the test data in Summary Table 8 of bolt lot CC (A354 BC)vs. lot ED (A354 BD) and by comparing lot DC (A354 BC) vs. lot FD (A354 BD) in both the compression and tension jigs. The bolt strengths and deformations may be compared because the nominal grips and diameters are the same. Figure 15 is a typical stress-deformation curve showing lot CC and ED and, for comparison lot 8B, which is an A325 bolt. All bolts were tested in 4 in.

A440 steel tension jigs. As was expected from a knowledge of the material properties of the bolts, the double shear strengths of the A354 BC and A354 BD or A490 bolts were higher than the shear strength of the A325 bolts.

From the data in Table 8, the double shear strength of A325 bolts tested in tension jigs was 72% of the bolt tensile strength. For A354 BC bolts, this percentage was 63% while for the A354 BD this percentage was 61%. Thus, the A325 bolts are stronger in shear, per pound of bolt tensile strength, than either the A354 BC and A354 BD or A490 bolt.

A comparison of the failures of the three types of fasteners is shown in Fig. 16. Referring to this figure, if one compares the ends of the bolts which are still intact, there is an apparent decrease in the relative shear displacement with increasing bolt strength. This would confirm the fact that the A325 bolts have more shear deformation capacity than either the A354 or the A490 bolts. However, as was noted earlier and can be seen visually in Fig. 8, the deformation of the bolts in tension jigs depends not only on the relative shearing displacement but also on the bending and bearing deformations in the bolt and in the connected plate material. Because of the relative increase in the shear strength, it was expected that, for a given connected material, the plate bearing deformations for the A490 bolts would be greater than for the A325 bolts. The results of this phenomena is that the total deformations for the three grades of bolts do not differ as much as one might expect. For the three bolt lots shown in Fig. 16, the total deformation at ultimate load was 0.183 in., 0.178 in. and 0.174 in. for the A325, A354 BC and A354 BD bolts, respectively. Similar results were obtained for the other bolt lots and testing conditions.

### 3.5 EFFECT OF BOLT DIAMETER

Two bolt diameters were tested, 7/8 in. and 1 in. diameter. The test data in Table 8 shows that the variation in ultimate shear stress as influenced by the bolt diameter is no greater than the variation in ultimate shear strengths between the various individual bolts tested. Thus, the data indicates that the bolt diameter has no appreciable effect on the ultimate shear strength. However, since the 1 in. bolt can sustain a higher ultimate load (in pounds), the bearing deformations for a 1 in. bolt were greater than the bearing deformations for a 7/8 in. bolt. Or, said another way, the shearing force increases at a greater rate than the increase in bearing area, thus causing higher bearing stresses and greater bearing deformations for the 1 in. bolt when compared to the 7/8 in. bolt. Therefore, the total deformations at ultimate load for a 1 in. bolt were greater than those for a 7/8 in. bolt when the plate thickness was maintained constant.

Figure 17 is a typical stress-deformation curve for 7/8 in. and 1 in. A354 BD bolts tested in A440 steel tension jigs. The figure shows that there is no appreciable difference in the ultimate shear strengths, but that the total deformation for the 1 in. bolt is greater than that for the 7/8 in. bolt, since the rate of increase of bearing area is only 14% while the rate of increase of shear area is 30%.

## 3.6 EFFECT OF CONNECTED MATERIAL

The effect of connected material on the ultimate shear strength and deformation is illustrated by comparing the test data in Tables 6 and 7 for bolts that have been tested in both A440 and Q & T steel jigs. Figure 18 is a typical shear-deformation curve showing the effect of this variable. It can be seen that the ultimate shear strengths are very nearly the same, but the total deformation for the bolt tested in the A440 steel jig is 0.116 inches greater than for the same bolt tested in Q & T steel jig or nearly double the value.

The test data shows that the variation in shear strength for a particular type of fastener as influenced by the type of connected material is no greater than the variation in shear strengths between the different bolt lots for a particular type of fastener. Thus, the test data indicates that the type of connected material has no influence on the ultimate shear strength.

However, because of the higher yield point of the Q & T material, the plate bearing deformations at ultimate load for a bolt tested in a jig made of Q & T steel will be less than if the same bolt were tested in a jig made of A440 steel. Figure 19 shows the main plates for tension test jigs made of A440 and Q & T steel in which the same lot of bolts was tested. Measurement of the final hole diameters show that the inelastic bearing deformations were larger in the A440 steel than in the Q & T steel. Figure 20 shows sawed sections of an A325 bolt in A440 steel and an A490 bolt in Q & T steel joints. Referring to this figure, more bolt bending and bearing deformation occurs in the A440 joint. The A490 bolt is rigidly sheared in the Q & T joint.

### 3.7 EFFECT OF GRIP AND LOADING SPAN

Research conducted on A141 rivets showed that with an increase in grip length, the ultimate shear strength of the rivet was reduced. This reduction was due to additional stresses caused by excessive bending of the rivets, i.e., the longer the rivet, the larger the bending deformations. Also, differences in the working of the rivet material during driving contributed to the reduction of ultimate shear strength. Thus, it was thought that an increase in grip length might possibly influence the shear strength of a high strength bolt.

This variable was investigated by comparing the behavior of a bolt installed in a 4 in. test jig (see Figs. 3a and 3b) to that of a bolt installed in an 8 in. test jig. The 8 in. jig was made by adding two 1 in. plates to the lap plates and two 1 in. plates to the main plates. In this manner, the ratio of loading span to grip was kept constant at ½. It should be noted, however, that this test jig configuration introduced two test variables: (1) the total grip length and (2) the loading span length.

The effect of loading span and grip length can be illustrated by comparing test data for lots ED and GD (A354 BD bolts) and is shown in

Fig. 21 for A440 steel tension jigs. The results shown in Fig. 21 were typical for the different test jigs and types of connected material. The difference in the ultimate shear strength and deformation at ultimate load were negligible.

Rumpf, in his investigation of A325 bolts, showed, by tests, that within the elastic and initially plastic portion of the load-deformation curve, the larger 8 in. grip bolts had larger deformations than the 4 in. grip bolts. However, all bolts had nearly the same ultimate shear strength and deformation at ultimate load regardless of the total grip length.

## 3.8 EFFECT OF END RESTRAINT

In a large bolted joint which contains many fasteners, the lap plates are restrained from bending freely between the interior fasteners. Hence, it was desirable to determine what effect the restraint of the free ends of the lap plate had on the ultimate shear strength and deformation of single bolted joints. Similar studies have been conducted on riveted aluminum joints[22]. If some way could be found to eliminate the lap plate prying action in a tension jig, the ultimate shear strength of a bolt tested in this manner should approach the ultimate shear strength of the same lot of bolts tested in a compression jig. In an effort to ascertain the significance of the lap plate prying and to determine why the tension jig tests yielded shear strengths that were 8 to 13% less than those obtained in a compression jig, special tests were conducted.

In tests of large bolted joints[6][7], it was visually obvious, as shown in Fig. 12, that only the end fasteners at the lap plate were subjected to the lap plate prying. Hence, the interior bolts may behave in a manner similar to that of a bolt installed in a compression jig.

Thus, it was decided to use the special tension jig as shown in Fig. 22 to eliminate lap plate prying. Referring to this figure, bolt "A" was installed in a slotted hole and carried none of the shear load, its only function being to keep the lap plates from bending outward. Only a small initial tension was induced into this bolt in order to minimize the frictional load transfer.

Three special tension jigs were fabricated from A440 steel and were used to test three 8B lot, A325 bolts. The results of these tests are shown in Fig. 23, which shows the average shear stress-deformation curve for the 8B lot bolts tested in compression jigs, standard tension jigs and the special tension jigs without lap plate prying. This figure shows that the ultimate shear strength for a bolt tested in a special tension jig from which lap plate prying is eliminated approaches the shear strength of a bolt tested in a compression jig. This result could be expected if one considers Eq. 2. When using the special tension jig, the tensile stress, $\sigma_t$ due to lap plate prying action, is about zero. Thus, the only tensile force is that induced by catenary action and this contribution is thought to be small[27] and is present in both type jigs. Therefore the bolt develops its full shear strength.

## 3.9 SCATTER OF RESULTS

For a number of tests, there was a fairly large scatter band. It was found that the maximum standard deviation from the mean ultimate shear strength was ± 6.0 ksi, which occurred for the DC lot tested in Q & T compression jigs. The maximum standard deviation from the mean deformation at ultimate load was ± 0.02 inches.

However, it can be seen from the test results in Tables 6 and 7 that the ultimate shear strengths and ultimate deformations were more consistent for tension jigs than for compression jigs, regardless of the connected material. The average standard deviation of ultimate load for A354 bolts tested in compression jigs was ± 4.30 kips, while for A354 bolts tested in tension jigs the average standard deviation was ± 2.90 kips. The same trend was observed for deformations at ultimate load, where for compression jigs the average standard deviation was ± 0.012 in., while for tension jigs the average standard deviation was ± 0.010 in.

There are a number of reasons why the test scatter was less for tension jig tests than for compression jig tests. A reverse lap plate prying action probably occurs in the compression jigs, with the result that, near ultimate, some of the load is being transferred by friction. This would not be true of the tension jigs, since lap plate prying would eliminate any frictional force.

# 4. MATHEMATICAL MODEL FOR THE STRESS-DEFORMATION RELATIONSHIP

## 4.1 ASSUMPTIONS

When a structural fastener is installed in a test jig as shown in Figs. 3a or 3b and subjected to shearing forces, the resulting load-deformation curve is a continuous function from zero load to ultimate load. Based on the results of typical bolt shear tests the required form of the mathematical model for the load-deformation relationship should closely simulate the load-deformation curve of an actual bolt test. That is, the relationship should be a linear one until inelastic deformations occur and thereafter it should become non-linear. The ultimate shear strength is assumed to be approached asymptotically. The reduction in strength observed after ultimate load is neglected.

Because of the highly complex behavior of the fastener and the surrounding material, even the elastic response of joints cannot be predicted on the basis of a rigorous theoretical treatment. Several investigators have developed semi-empirical relationships for this region[23][24][25].

No known analytical expressions have been developed for the elastic-inelastic load-deformation relationship of a fastener. All of the expressions have been confirmed to the elastic range in a form such as

$$R = \bar{K}\Delta \tag{3}$$

where the elastic constant has been determined from experimental data.

R is the load at an elastic deformation $\Delta$, while $\bar{K}$ is the elastic proportionality constant similar in function to Young's Modulus, E.

Fisher[26] has recently developed an analytical model for the relationship of a fastener in shear. The load-deformation relationship is approximated by the formula

$$R = K \ (1 - e^{-J\Delta})^{B} \tag{4}$$

where $0 \leq R \leq R_{ult}$ and $0 \leq \Delta \leq \Delta_{ult}$

$\Delta$ = total deformation of the bolt and bearing deformation of the connected material

e = base of the natural logarithm

K, J, B = regression analysis coefficients.

The following assumptions were made when developing Eq. 4[26]:

1. At zero loads the deformation should be zero.
2. For small values of deformations, the relationship between the load and deformation should be approximately linear.
3. As $\Delta$ approaches $\Delta_{ult}$, the bolt force increases at a decreasing rate.
4. The deformation $\Delta$ contains the components of shear, bending and bearing deformation of the fastener as well as the bearing deformation of the plate.

It can be seen that Eq. 4 satisfies all the above assumptions.

## 4.2 METHOD OF EVALUATION OF REGRESSION ANALYSIS COEFFICIENTS

The parameters K, J and B were evaluated by regression analysis and the boundary conditions. The analysis is described in Ref. 26. From this analysis, it was found that $K = R_{ult}$. Thus, the final shear (or load)-deformation relationship was found to be

$$R = R_{ult} (1 - e^{-J\Delta})^B \qquad (5)$$

where $R_{ult}$ = the ultimate shear strength.

Lehigh University's GE 225 computer was utilized to evaluate the coefficients J and B. Initial values of J could be guessed, through experience, quite closely. Then B was incremented through a range and the values of R and $\Delta$ were printed out for each set of J and B. A best fit was obtained when the squared residuals were minimized and the boundary condition $R = R_{ult}$ was satisfied.

The average values of $R_{ult}$, $\Delta_{ult}$, J and B are tabulated in Table 10. All coefficients were determined for the tension tests, since it was these results that were used to analyze the large bolted joints tested at Lehigh.

## 4.3 DISCUSSION OF RESULTS

Figure 24 shows the test data for ED lot, A354 BD bolts tested in an A440 steel tension jig. Also, Eq. 5 has been compared with the test data in Fig. 22. The theoretical curve is in excellent agreement with the test data, as was typical for all of the tests.

The values of $R_{ult}$, J and B are given in Table 10. The exponent B was seen to vary only slightly as changes in the connected material and bolt diameter occurred. However, there was a marked decrease in B when comparing A325 and A354 (or A490) bolts. For the A325 bolts, B varied from 0.95 to 1.0, with the majority of curves having B = 1.0. For the A354 and A490 bolts, the values of B varied somewhat more, but were still within a narrow range of 0.34 to 0.50. The values of J ranged from 18 to 28, with the majority falling within the 20 to 25 range.

It is thought that the values of B and J are a function of the type of connected material, bolt diameter, bolt type, etc. However, the test program that was conducted herein was not broad enough in scope to allow the evaluation of these variables. Therefore, additional studies employing many different bolt diameters and steel types are desirable if a generalized expression for J and B is to be developed.

# 5. SUMMARY AND CONCLUSIONS

This thesis presents the results of tests which demonstrated the behavior and performance of 7/8 in. and 1 in. A325, A354 BC and A354 BD (or A490) high strength bolts under double shear loading. Fasteners which have been tested in large bolted joints at Fritz Laboratory were loaded in this manner.

The most important aspect of this investigation was the determination of the effect of certain controlled variables upon the ultimate shear strength, and, of secondary importance, their effect on the deformation at ultimate load. In addition, a mathematical model had previously been developed which closely describes the behavior of a single bolt under shear loading. Certain parameters were determined which were used to analyze large bolted joints.

The following conclusions are based on the results of 81 tests of high strength A325, A354 BC, A354 BD and A490 bolts installed in test jigs which subjected the bolts to shear loading.

(1) The type of bolt head (heavy vs. regular head) had no significant effect on the ultimate shear strength of deformation at ultimate load.

(2) The ultimate shear strength of A354 BD (or A490) bolts tested in tension jigs was, on the average, 10% less than the same bolts tested in compression jigs. The reduction in shear strength was 10% for A354 BC bolts and 9% for A325 bolts. The actual bolt deforma-

tions at ultimate load were not affected by the type of testing device. (Fig. 10)

(3) The amount of initially induced bolt preload, as determined by measuring the bolt elongation, did not influence the ultimate shear strength of either A325 or A490 bolts. (Figs. 13, 14)

(4) The shear strength of A354 BD (or A490) bolts is 16% greater than the shear strength of A354 BC bolts and 25% greater than A325 bolts. (Fig. 15)

(5) There was no apparent influence of bolt diameter on the ultimate shear strength. However, because the bolt shearing area increases faster than the bolt bearing area, the deformations at ultimate load are greater for the 1 in. bolt than for the 7/8 in. bolt. (Fig. 17)

(6) The type of connected material had little if any influence on the ultimate shear strength. However, the higher yield point of the connected material results in a decrease in plate bearing deformations. (Figs. 18, 19).

(7) For a constant grip-loading span ratio of ½, the grip and loading span had no significant effect on the ultimate shear strength or deformation at ultimate load for either A325 or A354 BD bolts. (Fig. 21)

(8) When lap plate prying action in a tension jig was minimized, the shear strength of bolts tested in tension jigs approached the shear strength of bolts tested in compression jigs. (Fig. 23)

# 6. TABLES AND FIGURES

Table 1

BOLT CHEMICAL PROPERTIES

| Bolt Grade | Min. % Carbon | Min. % Manganese | Max. % Phosphorus | Max. % Sulphur |
|---|---|---|---|---|
| A325 | 0.30 | 0.50 | 0.04 | 0.05 |
| A354 | - | - | 0.04 | 0.04 |
| A490 | - | - | 0.04 | 0.04 |

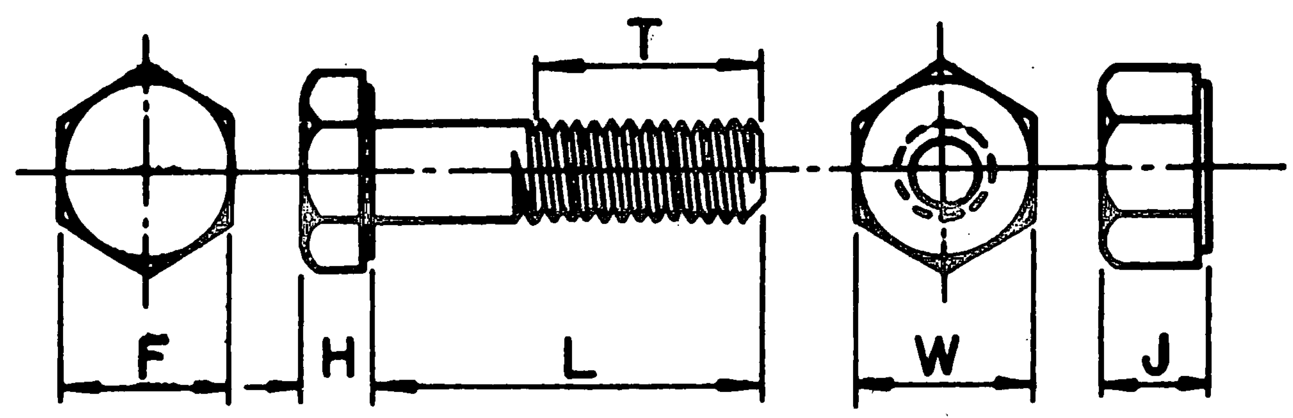
Table 2

0.505" COUPON TEST RESULTS

| Bolt Grade | Lot | Bolt Dia. | No.of Tests | 0.505" Tensile Strength | Bolt Tensile Strength | % Elong. in 2" ± | % Reduct. in area |
|---|---|---|---|---|---|---|---|
| A354 BC | AC | 7/8 | 3 | 140.3ksi | 140.8ksi | 21.2 | 57.2 |
| | CC | 7/8 | 3 | 133.0 | 134.8 | 21.6 | 62.2 |
| | DC | 1 | 3 | 131.6 | 137.0 | 22.6 | 63.1 |
| A354 BD | ED | 7/8 | 3 | 164.9 | 168.3 | 16.6 | 59.1 |
| | FD | 1 | 3 | 149.8 | 163.8 | 16.7 | 58.1 |
| | GD | 7/8 | 3 | 160.9 | 163.3 | 18.8 | 58.1 |
| A490 | KK | 7/8 | 3 | 153.4 | 168.6 | 20.0 | 55.5 |
| A325 | 8B | 7/8 | 3 | 106.8 | 115.2 | 21.0 | - |

Table 3

BOLT DESCRIPTION




| BOLT | | | | | | | NUT | |
|---|---|---|---|---|---|---|---|---|
| Bolt Grade | Lot | Dia. | Length L | Width Across Flats,F | Height H | Thread Length, T | Width Across Flats,W | Height J |
| A354 BC | AC | 7/8 | 5¼ | 1-7/16 | 35/64 | 1½ | 1-7/16 | 55/64 |
| A354 BC | CC | 7/8 | 5¼ | 1-5/16 | 35/64 | 2 | 1-5/16 | 3/4 |
| A354 BC | DC | 1 | 5½ | 1½ | 39/64 | 2¼ | 1½ | 55/64 |
| A354 BD | ED | 7/8 | 5½ | 1-5/16 | 35/64 | 2 | 1-5/16 | 3/4 |
| A354 BD | FD | 1 | 5½ | 1½ | 39/64 | 2¼ | 1½ | 55/64 |
| A354 BD | GD | 7/8 | 9½ | 1-5/16 | 35/64 | 2¼ | 1-5/16 | 3/4 |
| A490 | KK | 7/8 | 5½ | 1-7/16 | 35/64 | 1½ | 1-7/16 | 55/64 |
| A490 | JJ | 1 | 5½ | 1-5/8 | 39/64 | 1-3/4 | 1-5/8 | 63/64 |
| A325 | 8B | 7/8 | 5½ | 1-7/16 | 35/64 | 1½ | 1-7/16 | 55/64 |

Table 4

RESULTS OF COUPON TESTS

| Steel | Number of Coupons | Static Yield Stress,ksi | Ultimate Tensile Stress,ksi | % Elong. in 8". | % Red. in Area |
|---|---|---|---|---|---|
| A440 | 40 | 42.9 | 75.8 | 28.0 | 62.4 |
| Q & T | 6 | 110.3 | 119.9 | 12.6 | 54.4 |

Table 5

THE TESTING PROGRAM

| Bolt Grade | Lot | Dia. | Head* | Length Under Head | Thread Length | Grip | Jigs Tested | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | A440 Comp. | A440 Tens. | Q & T Comp. | Q & T Tens. |
| A354 BC | AC | 7/8 | H | 5¼ | 1½ | 4-1/8 | 3 | - | 3 | - |
| | CC | 7/8 | R | 5½ | 2 | 4¼ | 3 | 3 | 3 | 3 |
| | DC | 1 | R$^{o}$ | 5½ | 2¼ | 4-1/8 | 3 | 3 | 3 | 3 |
| A354 BD | ED | 7/8 | R | 5½ | 2 | 4¼ | 3 | 3 | 3 | 3 |
| | FD | 1 | R$^{o}$ | 5½ | 2¼ | 4-1/8 | 3 | 3 | 3 | 3 |
| | GD | 7/8 | R | 9½ | 2¼ | 8¼ | 3 | 3 | 3 | 3 |
| A490 | KK | 7/8 | H | 5½ | 1½ | 4-1/8 | 3 | 3 | - | - |
| | JJ | 1 | H | 5½ | 1-3/4 | 4-1/8 | - | - | - | 3 |
| A325 | 8B | 7/8 | H | 5½ | 1½ | 4-1/8 | 3 | 3 | - | - |

* H - Heavy Head

R - Regular Head

o - Machined to avoid shear plane through thread runout.

Table 6

INDIVIDUAL BOLT TEST RESULTS
FOR COMPRESSION JIGS

| Bolt Lot and No. | Bolt Dia. | Steel | Ultimate Strength, kips | Deform at Ult., inches | Fracture Load, kips | Deform at Fracture inches |
|---|---|---|---|---|---|---|
| 1. A354 BC Bolts | | | | | | |
| AC-12 | 7/8 | A440 | 119.4 | .2465 | 92 | .265 |
| AC- 2 | 7/8 | A440 | 114.0 | .2141 | 50 | .270 |
| AC-32 | 7/8 | A440 | 114.5 | .2044 | 82 | .245 |
| Ave. AC | 7/8 | A440 | 116.0 | .2217 | 75 | .260 |
| AC-25 | 7/8 | Q & T | 119.3 | .1662 | 80 | .195 |
| AC-18 | 7/8 | Q & T | 110.2 | .1441 | 77 | .178 |
| AC- 4 | 7/8 | Q & T | 117.3 | .1647 | 100 | .224 |
| Ave. AC | 7/8 | Q & T | 115.6 | .1583 | 86 | .199 |
| CC-37 | 7/8 | A440 | 112.5 | .2024 | 90 | .216 |
| CC- 1 | 7/8 | A440 | 120.3 | .2174 | 80 | .258 |
| CC-15 | 7/8 | A440 | 118.1 | .2232 | 104 | .243 |
| Ave. CC | 7/8 | A440 | 117.0 | .2143 | 91 | .239 |
| CC- 3 | 7/8 | Q & T | 108.6 | .1561 | 72 | .192 |
| CC-31 | 7/8 | Q & T | 110.9 | .1610 | 50 | .211 |
| CC-19 | 7/8 | Q & T | 109.8 | .1651 | 66 | .200 |
| Ave. CC | 7/8 | Q & T | 109.8 | .1607 | 63 | .201 |
| DC-28 | 1 | A440 | 148.6 | .2599 | 124 | .276 |
| DC-35 | 1 | A440 | 150.5 | .2400 | 120 | .277 |
| DC-12 | 1 | A440 | 144.8 | .2290 | 120 | .260 |
| Ave. DC | 1 | A440 | 147.9 | .2429 | 121 | .271 |
| DC- 9 | 1 | Q & T | 152.3 | .1765 | 128 | .207 |
| DC-11 | 1 | Q & T | 142.2 | .1600 | 89 | .211 |
| DC-10 | 1 | Q & T | 161.0 | .1700 | 141 | .194 |
| Ave. DC | 1 | Q & T | 151.8 | .1688 | 119 | .204 |
| 2. A354 BD bolts | | | | | | |
| ED-20 | 7/8 | A440 | 128.8 | .1796 | 115 | .199 |
| ED- 1 | 7/8 | A440 | 132.7 | .1934 | 93 | .260 |
| ED-11 | 7/8 | A440 | 134.2 | .1700 | 124 | .180 |
| Ave. ED | 7/8 | A440 | 131.2 | .1810 | 111 | .213 |
| ED- 3 | 7/8 | Q & T | 145.7 | .1530 | 136 | .165 |
| ED- 7 | 7/8 | Q & T | 141.1 | .1435 | 128 | .160 |
| ED-30 | 7/8 | Q & T | 130.7 | .1480 | 121 | .157 |
| Ave. ED | 7/8 | Q & T | 139.2 | .1482 | 128 | .161 |

Table 6 (cont'd)

| Bolt Lot and No. | Bolt Dia. | Steel | Ultimate Strength, kips | Deform at Ult., inches | Fracture Load, kips | Deform at Fracture inches |
|---|---|---|---|---|---|---|
| FD- 2 | 1 | A440 | 177.4 | .2100 | 161 | .225 |
| FD- 3 | 1 | A440 | 181.0 | .2300 | 160 | .250 |
| FD- 9 | 1 | A440 | 183.3 | .2480 | 160 | .267 |
| Ave. FD | 1 | A440 | 180.6 | .2293 | 160 | .247 |
| FD-14 | 1 | Q & T | 176.6 | .1642 | 168 | .177 |
| FD-29 | 1 | Q & T | 169.3 | .1768 | 153 | .196 |
| FD-20 | 1 | Q & T | 179.0 | .1870 | 160 | .205 |
| Ave. FD | 1 | Q & T | 174.9 | .1760 | 160 | .193 |
| GD- 8 | 7/8 | A440 | 139.3 | .1989 | 120 | .225 |
| GD-40 | 7/8 | A440 | 133.7 | .1852 | 125 | .198 |
| GD-22 | 7/8 | A440 | 131.7 | .2036 | 120 | .225 |
| Ave. GD | 7/8 | A440 | 134.9 | .1959 | 122 | .216 |
| GD- 6 | 7/8 | Q & T | 146.6 | .1359 | 133 | .162 |
| GD-28 | 7/8 | Q & T | 137.3 | .1650 | 126 | .179 |
| GD-20 | 7/8 | Q & T | 136.8 | .1490 | 131 | .157 |
| Ave. GD | 7/8 | Q & T | 140.2 | .1500 | 130 | .166 |
| 3. A490 Bolts | | | | | | |
| KK-34 | 7/8 | A440 | 137.5 | .2744 | 90 | - |
| KK-63 | 7/8 | A440 | 140.0 | .2662 | 125 | .286 |
| KK-14 | 7/8 | A440 | 135.0 | .2479 | 108 | - |
| Ave. KK | 7/8 | A440 | 137.5 | .2628 | 108 | .286 |
| 4. A325 Bolts | | | | | | |
| 8B-29 | 7/8 | A440 | 102.9 | .262 | 42 | .292 |
| 8B-34 | 7/8 | A440 | 103.2 | .228 | 80 | .242 |
| 8B-137 | 7/8 | A440 | 105.9 | .260 | 85 | .283 |
| Ave. 8B | 7/8 | A440 | 104.0 | .250 | 72 | .272 |

Table 7

INDIVIDUAL BOLT TEST RESULTS
FOR TENSION JIGS

| Bolt Lot and No. | Bolt Dia. | Steel | Ultimate Strength, kips | Deform at Ult., inches | Fracture Load, kips | Deform at Fracture inches |
|---|---|---|---|---|---|---|
| 1. A354 BC Bolts | | | | | | |
| CC-13 | 7/8 | A440 | 102.8 | .1781 | 93 | .205 |
| CC-27 | 7/8 | A440 | 104.9 | .1904 | 100 | .201 |
| CC-10 | 7/8 | A440 | 103.5 | .1658 | 90 | .185 |
| Ave. CC | 7/8 | A440 | 103.7 | .1781 | 94 | .197 |
| CC-11 | 7/8 | Q & T | 101.2 | .1432 | 89 | .157 |
| CC-28 | 7/8 | Q & T | 101.3 | .1433 | 87 | .168 |
| CC-20 | 7/8 | Q & T | 100.9 | .1248 | 83 | .160 |
| Ave. CC | 7/8 | Q & T | 101.1 | .1371 | 86 | .162 |
| DC-39 | 1 | A440 | 138.5 | .2135 | 133 | .233 |
| DC- 4 | 1 | A440 | 140.4 | .1950 | 130 | .205 |
| DC-16 | 1 | A440 | 135.8 | .2284 | 125 | .245 |
| Ave. DC | 1 | A440 | 138.2 | .2123 | 129 | .228 |
| DC-38 | 1 | Q & T | 130.7 | .1488 | 118 | .181 |
| DC- 7 | 1 | Q & T | 132.5 | .1632 | 122 | .179 |
| DC-36 | 1 | Q & T | 131.2 | .1572 | 120 | .213 |
| Ave. DC | 1 | Q & T | 131.5 | .1564 | 122 | .191 |
| 2. A354 BD Bolts | | | | | | |
| ED-32 | 7/8 | A440 | 124.5 | .1800 | 113 | .200 |
| ED-24 | 7/8 | A440 | 123.2 | .1677 | 108 | .221 |
| ED-12 | 7/8 | A440 | 124.0 | .1732 | 115 | .203 |
| Ave. ED | 7/8 | A440 | 123.9 | .1736 | 112 | .208 |
| ED-10 | 7/8 | Q & T | 128.8 | .1192 | 103 | .160 |
| ED-35 | 7/8 | Q & T | 120.0 | .1165 | 115 | .128 |
| ED-29 | 7/8 | Q & T | 120.7 | .1033 | 101 | .142 |
| Ave. ED | 7/8 | Q & T | 123.2 | .1130 | 106 | .143 |
| FD-13 | 1 | A440 | 151.2 | .2474 | 130 | .279 |
| FD-5 | 1 | A440 | 156.3 | .2557 | 132 | .292 |
| FD-27 | 1 | A440 | 165.7 | .2233 | 152 | .252 |
| Ave. FD | 1 | A440 | 157.7 | .2476 | 138 | .274 |
| FD-31 | 1 | Q & T | 160.7 | .1357 | 155 | .145 |
| FD-28 | 1 | Q & T | 152.0 | .1327 | 143 | .162 |
| FD-30 | 1 | Q & T | 157.5 | .1253 | 145 | .150 |
| Ave. FD | 1 | Q & T | 156.6 | .1312 | 148 | .152 |

Table 7 (cont'd)

| Bolt Lot and No. | Bolt Dia. | Steel | Ultimate Strength, kips | Deform at Ult., inches | Fracture Load, kips | Deform at Fracture inches |
|---|---|---|---|---|---|---|
| GD-39 | 7/8 | A440 | 120.5 | .1706 | 112 | .190 |
| GD-37 | 7/8 | A440 | - | .1836 | - | - |
| GD-26 | 7/8 | A440 | 124.2 | .1632 | 110 | .195 |
| Ave. GD | 7/8 | A440 | 122.2 | .1725 | 111 | .192 |
| GD-11 | 7/8 | Q & T | 123.5 | .1408 | - | - |
| GD- 6 | 7/8 | Q & T | 122.5 | .1377 | - | - |
| GD-26 | 7/8 | Q & T | 124.3 | .1760 | - | - |
| Ave. GD | 7/8 | Q & T | 123.4 | .1515 | - | - |
| 3. A490 Bolts | | | | | | |
| KK-38 | 7/8 | A440 | 124.0 | .2008 | 110 | - |
| KK-35 | 7/8 | A440 | 125.1 | .2139 | 120 | - |
| KK-54 | 7/8 | A440 | 124.2 | .1910 | 115 | - |
| Ave. KK | 7/8 | A440 | 124.4 | .2019 | 115 | - |
| JJ-14 | 1 | Q & T | 151.2 | .1703 | 148 | .215 |
| JJ-52 | 1 | Q & T | 149.0 | .1491 | 145 | .160 |
| JJ-1 | 1 | Q & T | 154.9 | .1448 | - | - |
| Ave. JJ | 1 | Q & T | 151.7 | .1547 | 147 | .188 |
| 4. A325 Bolts | | | | | | |
| 8B-109 | 7/8 | A440 | 94.0 | .2000 | 75 | - |
| 8B-12 | 7/8 | A440 | 90.0 | .1730 | 74 | .181 |
| 8B-188 | 7/8 | A440 | 93.3 | .1760 | 76 | .195 |
| Ave. 8B | 7/8 | A440 | 92.4 | .1830 | 75 | .188 |

## Table 8

### Summary of Test Results

| Bolt Grade | Lot | Dia. | Compression Jig: Ultimate Shear Stress, ksi | | | Compression Jig: Deform. At Ultimate, inches | | Tension Jig: Ultimate Shear Stress, ksi | | | Tension Jig: Deform. At Ultimate, inches | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A440 | Q & T | Avg. | A440 | Q & T | A440 | Q & T | Avg. | A440 | Q & T |
| A354BC | AC | 7/8 | 96.6 | 96.4 | 96.5 | .2217 | .1583 | - | - | - | - | - |
| | CC | 7/8 | 97.3 | 91.3 | 94.3 | .2143 | .1607 | 86.3 | 84.2 | 85.2 | .1781 | .1371 |
| | DC | 1 | 94.2 | 96.6 | 95.4 | .2429 | .1688 | 88.0 | 83.7 | 85.9 | .2123 | .1564 |
| A354BD | ED | 7/8 | 110.0 | 116.0 | 113.0 | .1810 | .1482 | 103.3 | 102.7 | 103.0 | .1736 | .1130 |
| | FD | 1 | 115.0 | 111.4 | 113.2 | .2293 | .1760 | 100.3 | 99.7 | 100.0 | .2476 | .1312 |
| | GD | 7/8 | 112.3 | 116.8 | 114.1 | .1959 | .1500 | 102.0 | 102.9 | 102.5 | .1725 | .1515 |
| A490 | KK | 7/8 | 114.5 | - | 114.5 | .2628 | - | 103.8 | - | 103.8 | .2019 | - |
| | JJ | 1 | - | - | - | - | - | - | 96.5 | 96.5 | - | .1547 |
| A325 | 8B | 7/8 | 86.7 | - | 86.7 | .250 | - | 76.9 | - | 76.9 | .1830 | - |

Note: All the stresses and deformations are the average of three tests.

Table 9

MINIMUM BOLT SHEAR STRENGTHS

Minimum Shear Strengths, Ksi.

| Bolt Grade | Lot | Dia. | Bolt Tensile Strength* | Compression Jig | | | Tension Jig | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | A440 | Q & T | Avg. | A440 | Q & T | Avg. |
| A354 BC | AC | 7/8 | 140.8ksi | 85.9 | 85.5 | 85.7 | - | - | - |
| | CC | 7/8 | 134.8 | 90.2 | 84.6 | 87.4 | 80.0 | 78.0 | 79.0 |
| | DC | 1 | 137.0 | 85.9 | 88.0 | 87.0 | 80.5 | 76.4 | 78.4 |
| A354 BD | ED | 7/8 | 168.3 | 98.0 | 103.2 | 100.6 | 92.0 | 91.4 | 91.7 |
| | FD | 1 | 163.8 | 105.3 | 102.0 | 103.7 | 91.9 | 91.3 | 91.6 |
| | GD | 7/8 | 163.3 | 103.0 | 107.0 | 105.0 | 93.5 | 94.5 | 94.0 |
| A490 | KK | 7/8 | 168.6 | 102.0 | - | 102.0 | 92.1 | - | 92.1 |
| | JJ | 1 | 163.5 | - | - | - | - | 88.7 | 88.7 |
| A325 | 8B | 7/8 | 115.2 | 86.5 | - | 86.5 | 76.7 | - | 76.7 |

* Based on tests of full size bolts. The tensile strength was computed as $P/A_s$ where:

$$A_s = 0.7854 \left(D - \frac{0.9743}{n}\right)^2$$

$A_s$ = tensile stress area

D = nominal bolt diameter

n = threads per inch

P = average ultimate tensile strength

Table 10

SUMMARY OF TEST RESULTS AND
ANALYSIS OF A325, A354 AND A490 BOLTS

| Bolt Grade | Lot | Dia. | Connected Material | Test Jig | Ultimate Strength, $R_{ULT}$, kips | Ultimate Deform. inches | Bolt Parameters J | Bolt Parameters B |
|---|---|---|---|---|---|---|---|---|
| A325 | 8A* | 7/8 | A440 | Tension | 98.6 | .187 | 23 | 1 |
| A325 | 8B | 7/8 | A440 | Tension | 92.5 | .200 | 25 | .95 |
| A325 | H* | 7/8 | A440 | Tension | 95.2 | .220 | 22 | 1 |
| A325 | C* | 7/8 | A7 | Tension | 98.5 | .238 | 18 | 1 |
| A325 | D* | 7/8 | A7 | Tension | 101.8 | .279 | 18 | 1 |
| A354 BC | CC | 7/8 | A440 | Tension | 103.7 | .1781 | 20 | .38 |
| A354 BC | CC | 7/8 | Q & T | Tension | 101.1 | .1371 | 25 | .42 |
| A354 BC | DC | 1 | A440 | Tension | 138.2 | .2123 | 20 | .50 |
| A354 BC | DC | 1 | Q & T | Tension | 131.5 | .1564 | 25 | .50 |
| A354 BD | ED | 7/8 | A440 | Tension | 123.9 | .1736 | 25 | .42 |
| A354 BD | ED | 7/8 | Q & T | Tension | 123.2 | .1130 | 25 | .42 |
| A354 BD | FD | 1 | A440 | Tension | 157.7 | .2476 | 21 | .50 |
| A354 BD | GD | 7/8 | A440 | Tension | 122.4 | .1725 | 23 | .50 |
| A354 BD | GD | 7/8 | Q & T | Tension | 123.4 | .1515 | 25 | .34 |
| A490 | KK | 7/8 | A440 | Tension | 124.4 | .2019 | 23 | .40 |
| A490 | JJ | 1 | Q & T | Tension | 151.7 | .1547 | 28 | .36 |

* Values taken from Ref. 19.

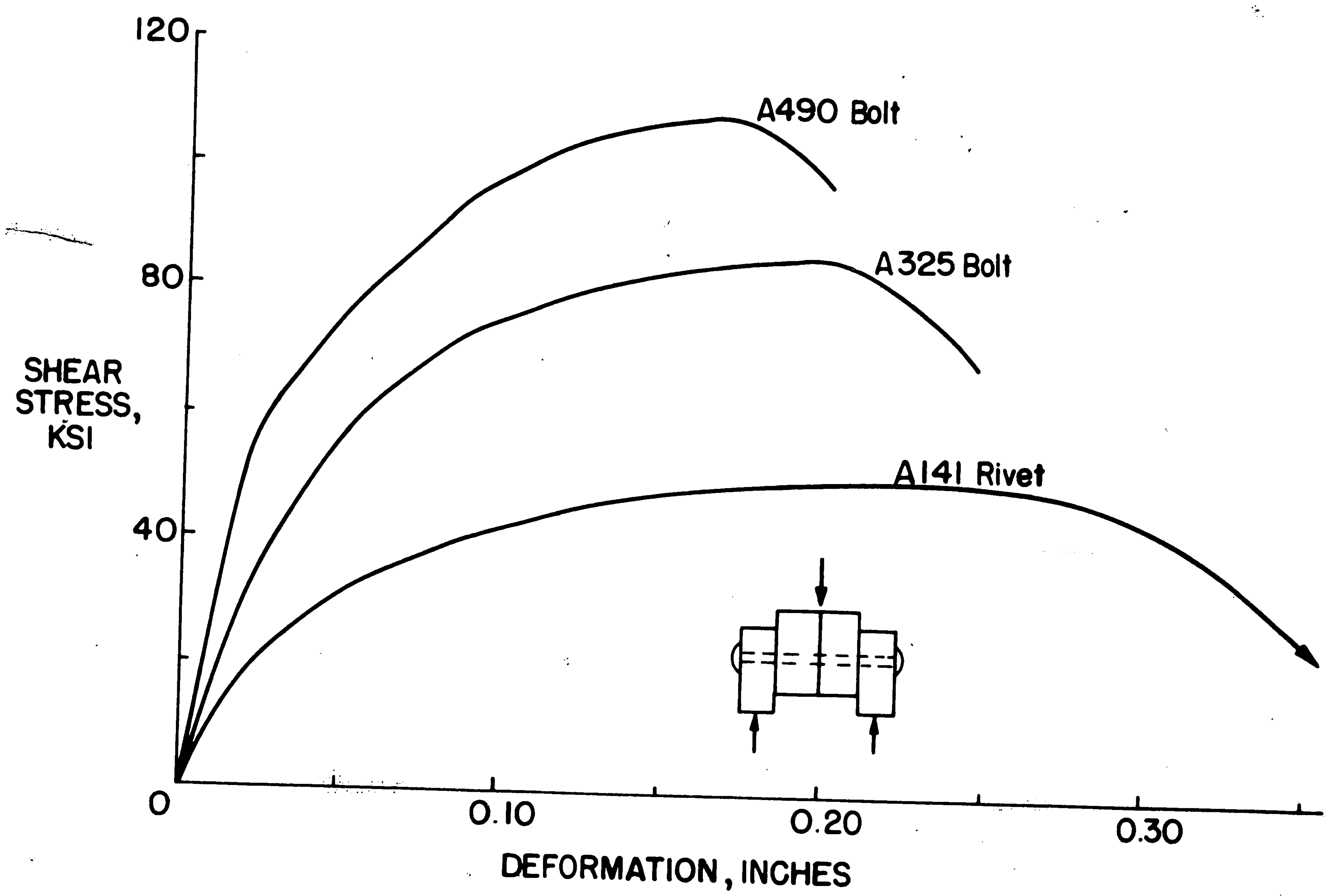
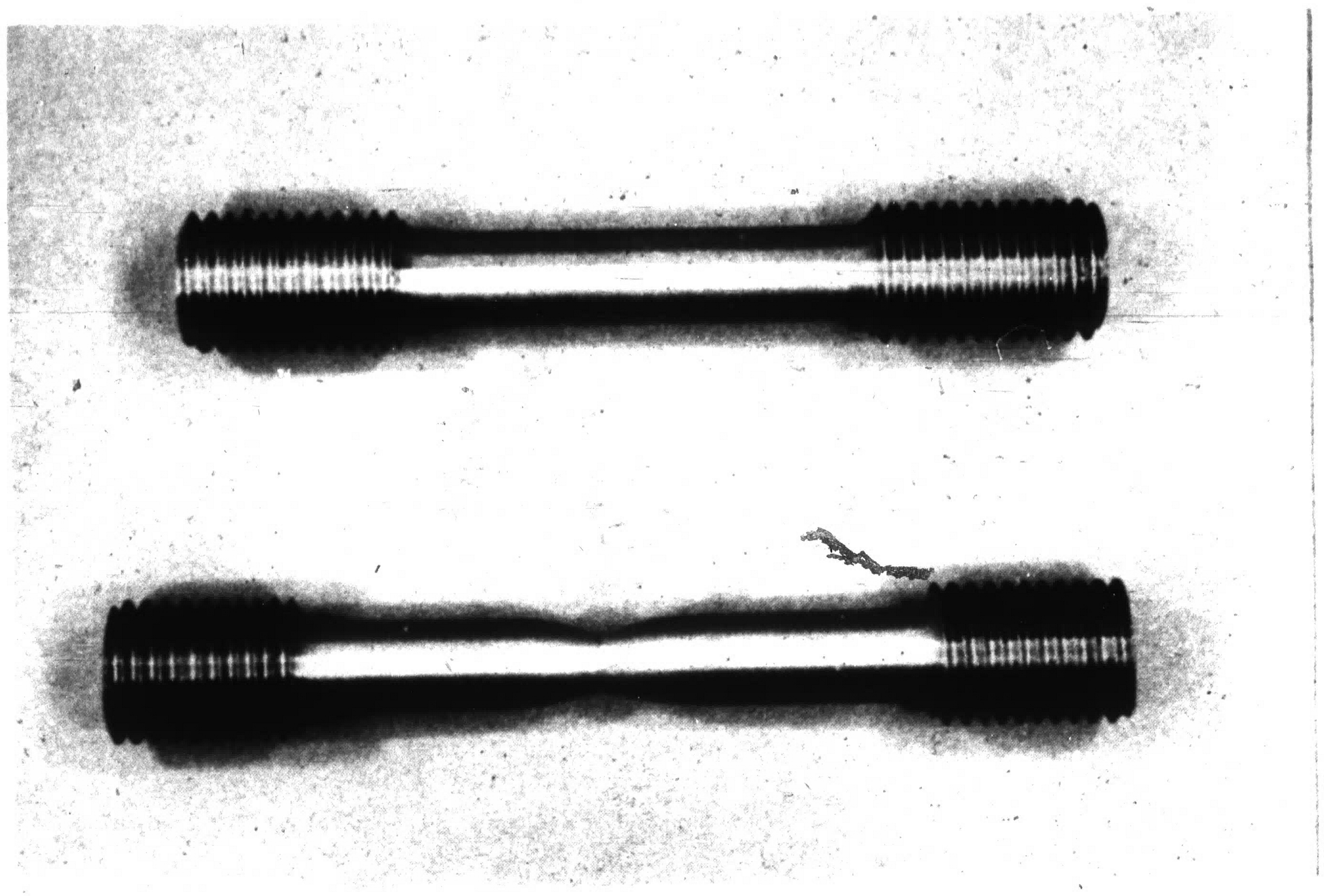



Fig. 1 Stress-Deformation Curves for A325 and A490 Bolts and A141 Rivets



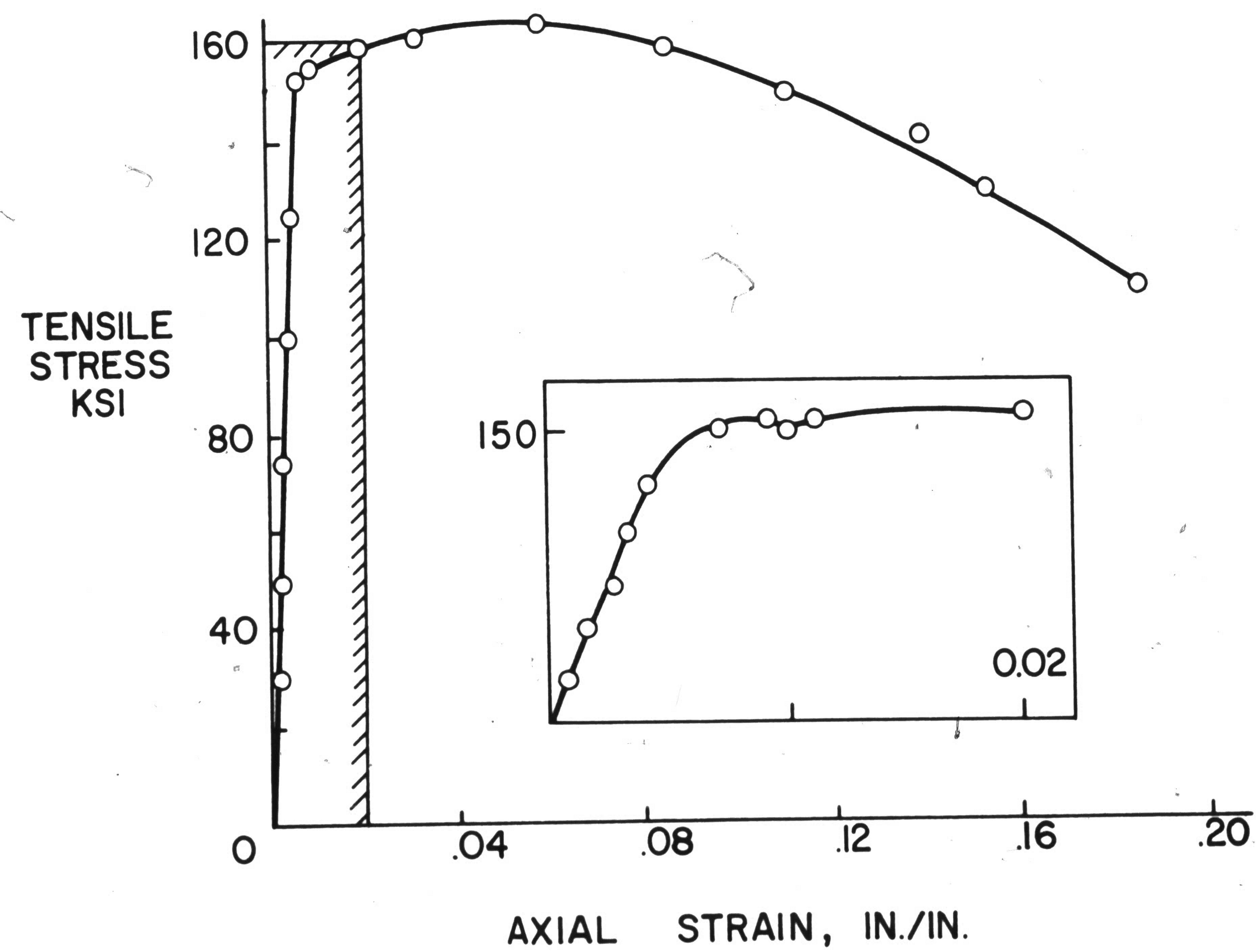



Fig. 2 Typical Stress-Strain Curve for a 0.505" Tensile Coupon

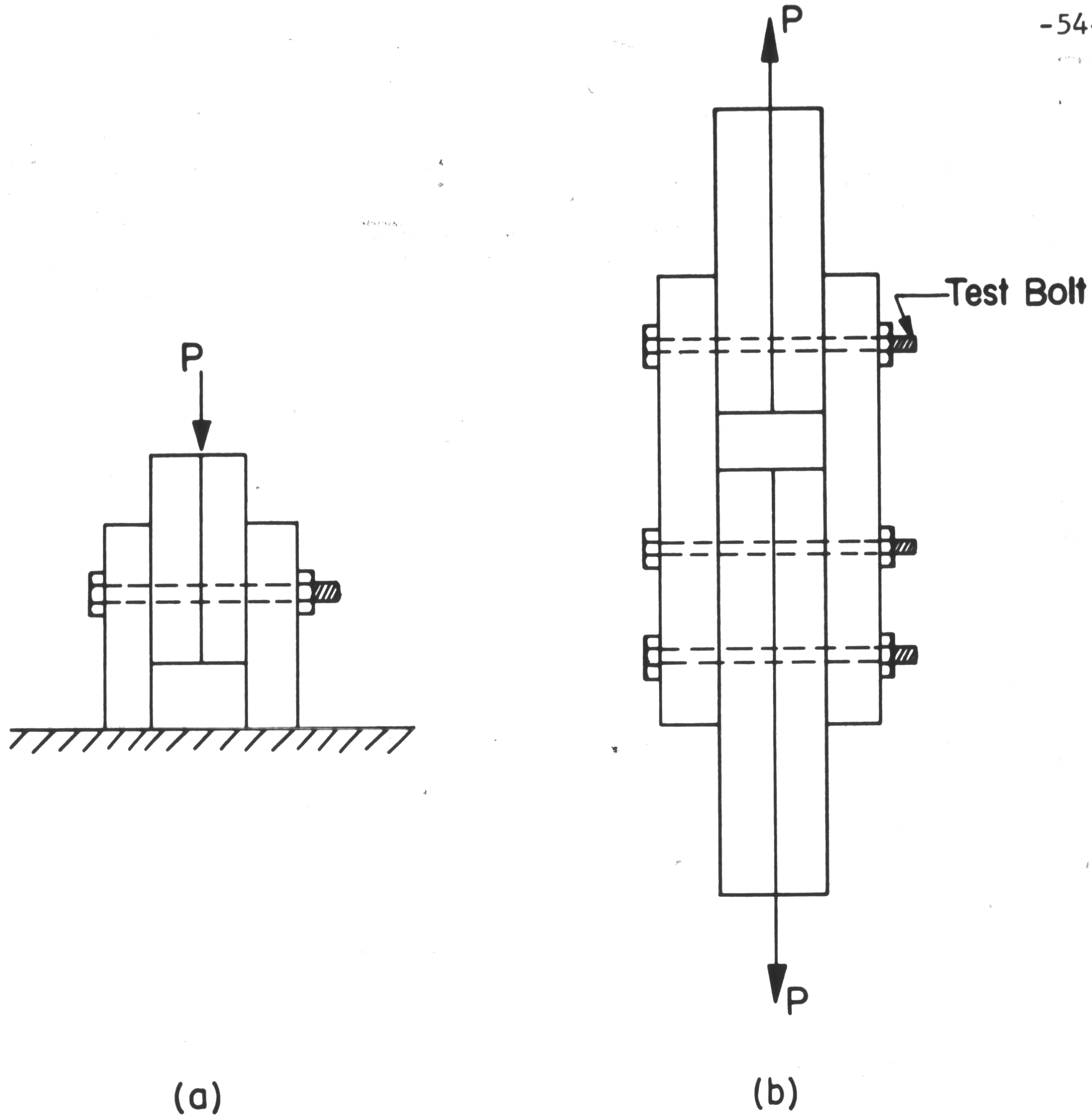



Fig. 3 4" Compression and Tension Test Jigs

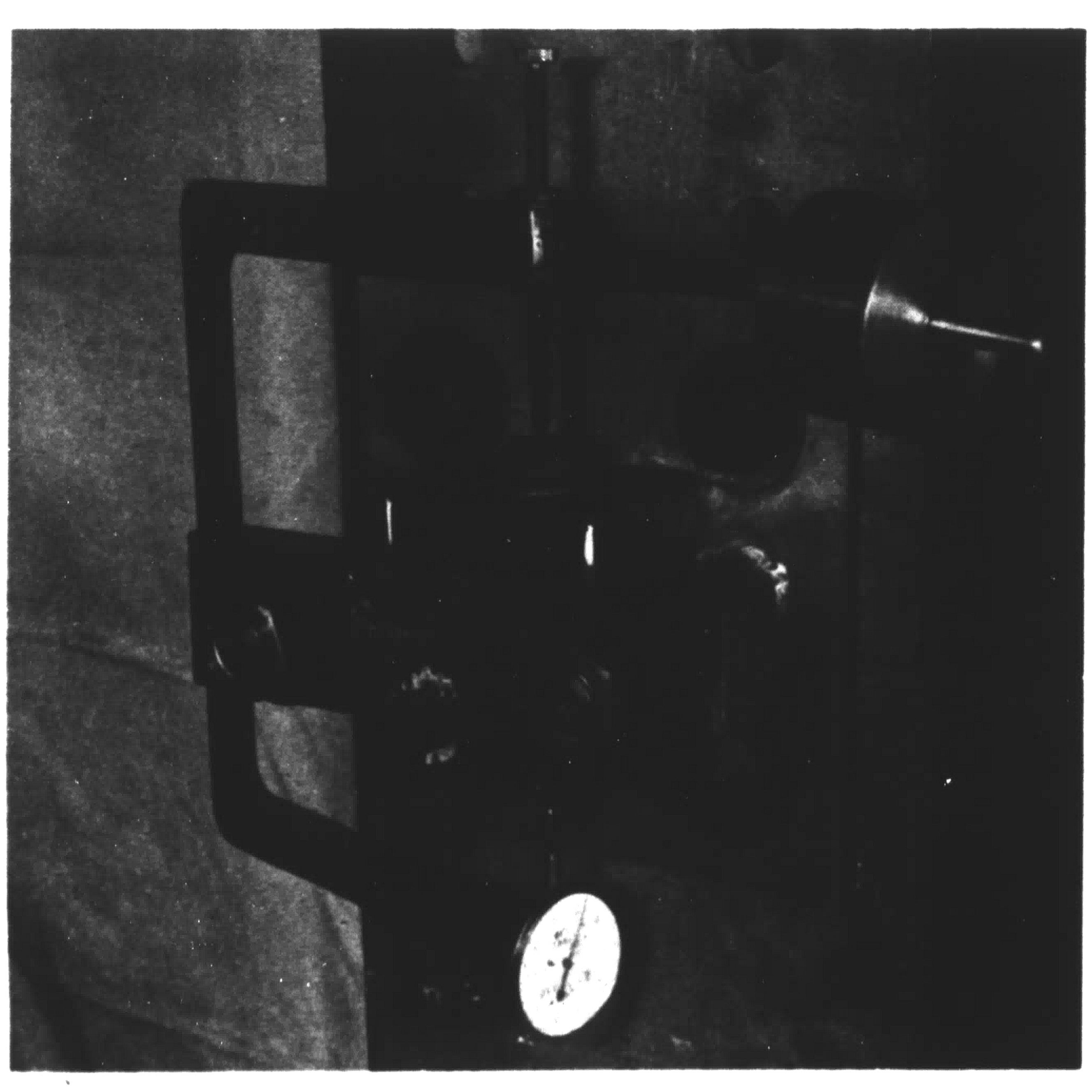


Fig. 4 Measuring Bolt Elongation on a Bolting Up Fixture

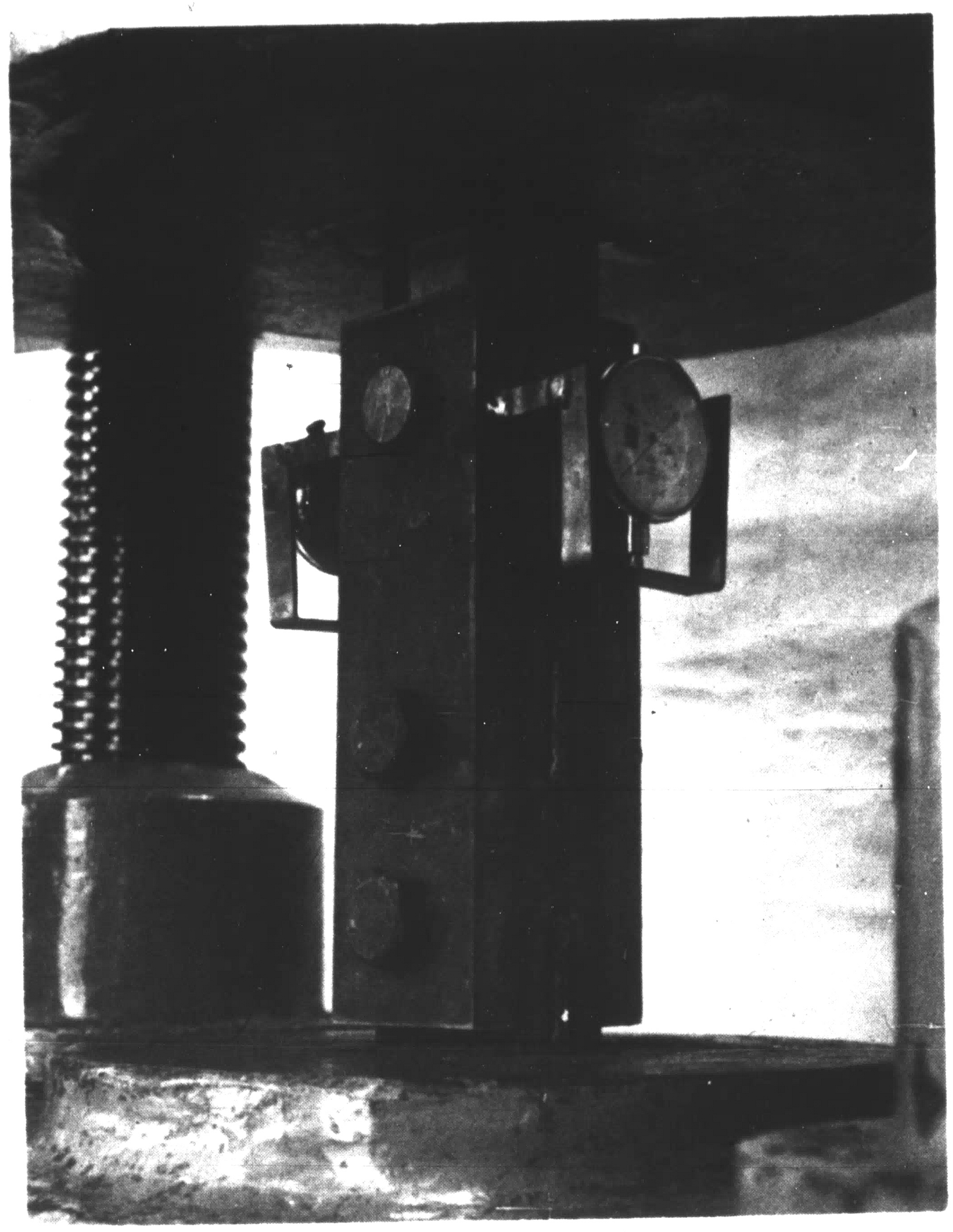


Fig. 5 Tension Jig Instrumentation

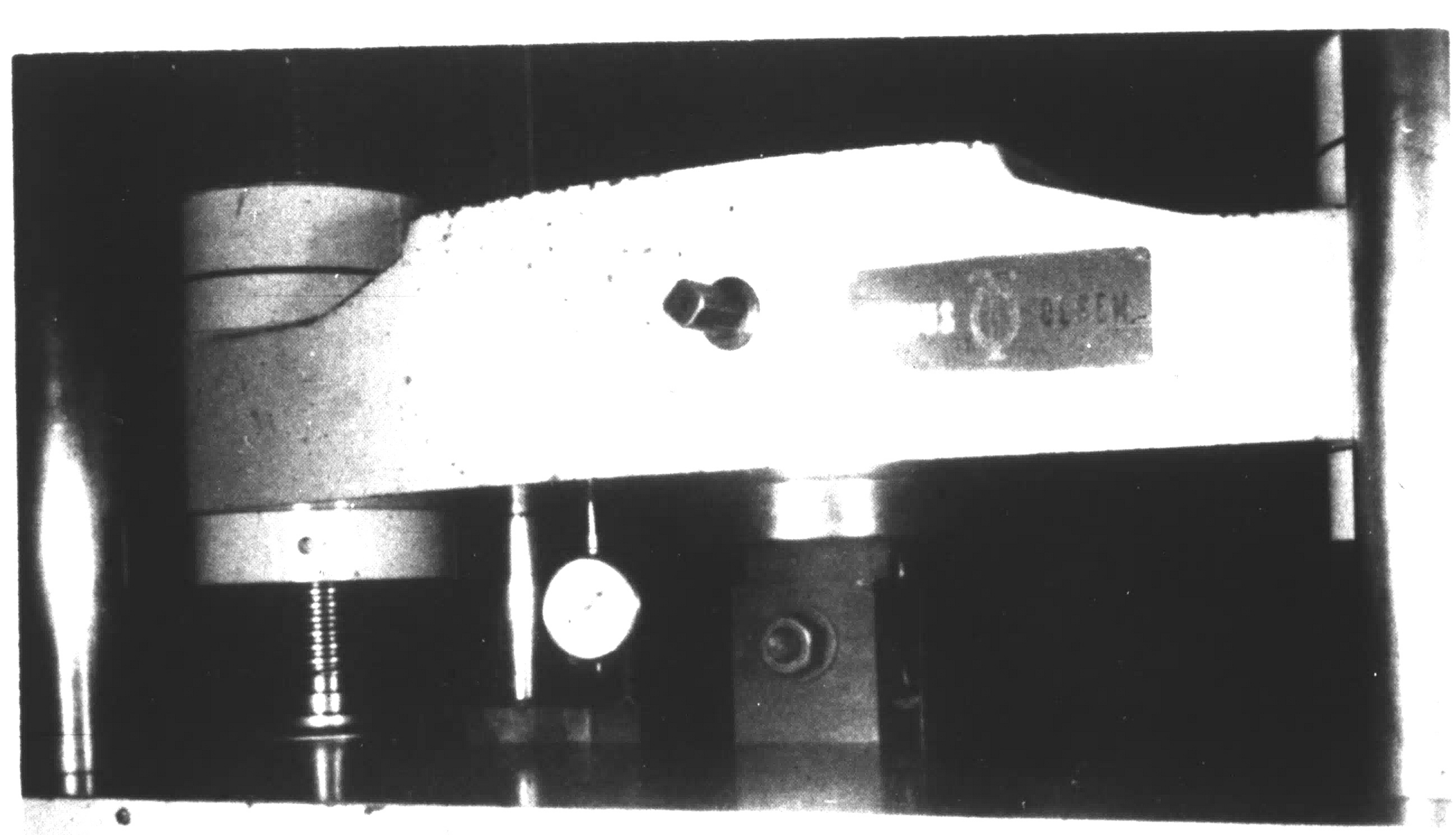


Fig. 6 Compression Jig Instrumentation

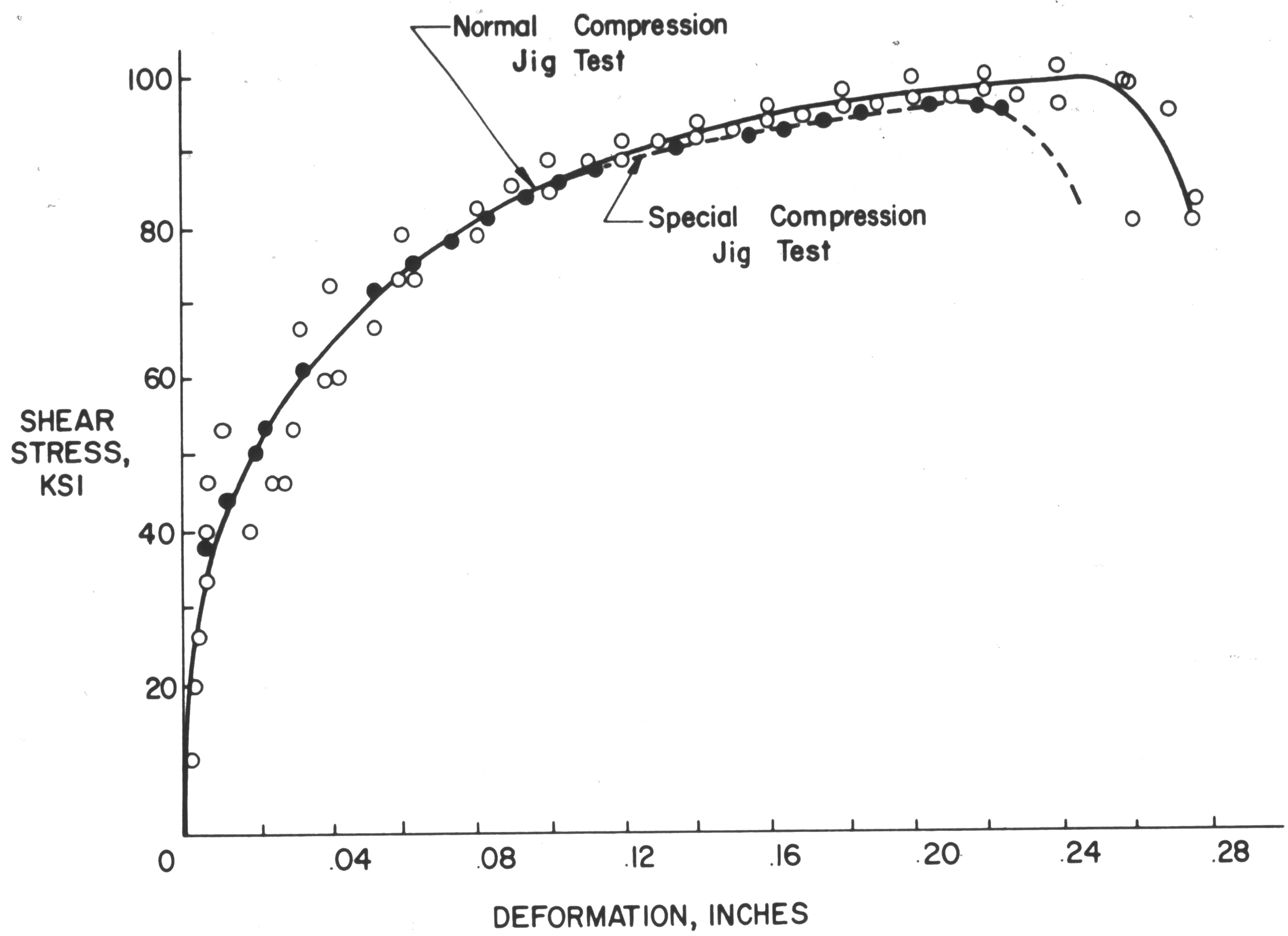



Fig. 7 Effect of Deformations within the Compression Jig Assembly on the Deformation at Ultimate Load

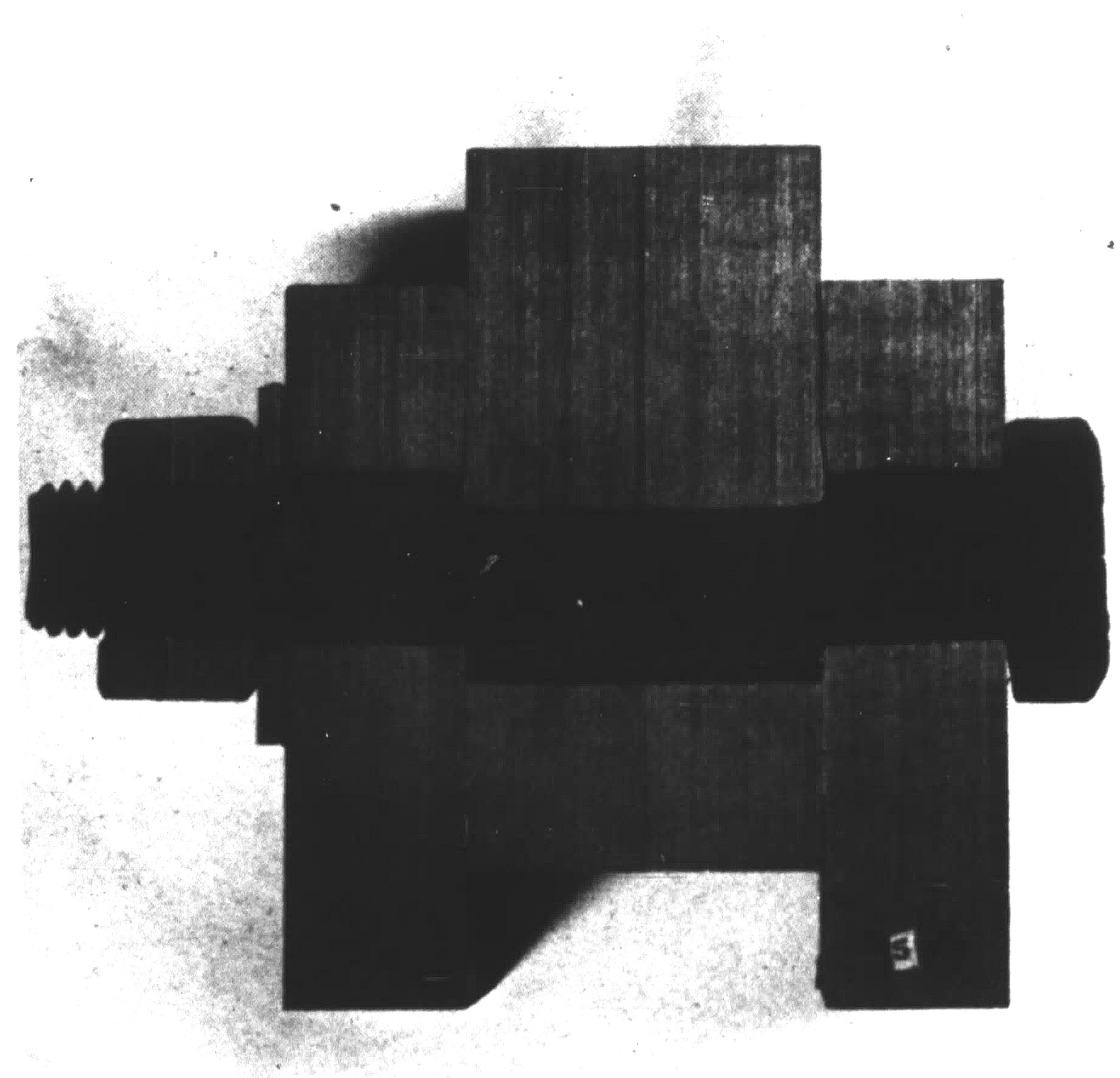


Fig. 8 Sawed Section of a Single A325 Bolt

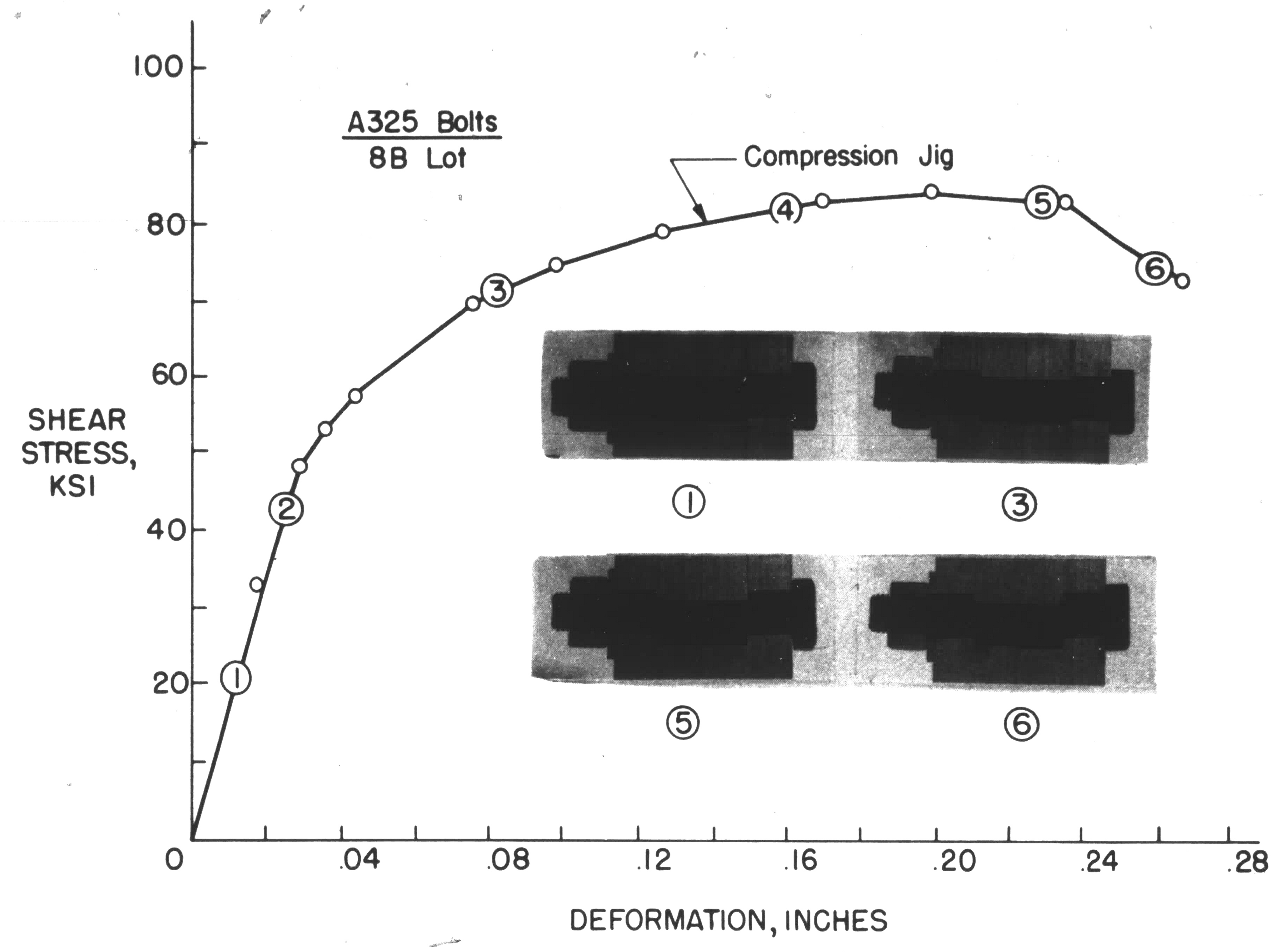



Fig. 9 Deformation of A325 Bolts at Various Stages of Loading

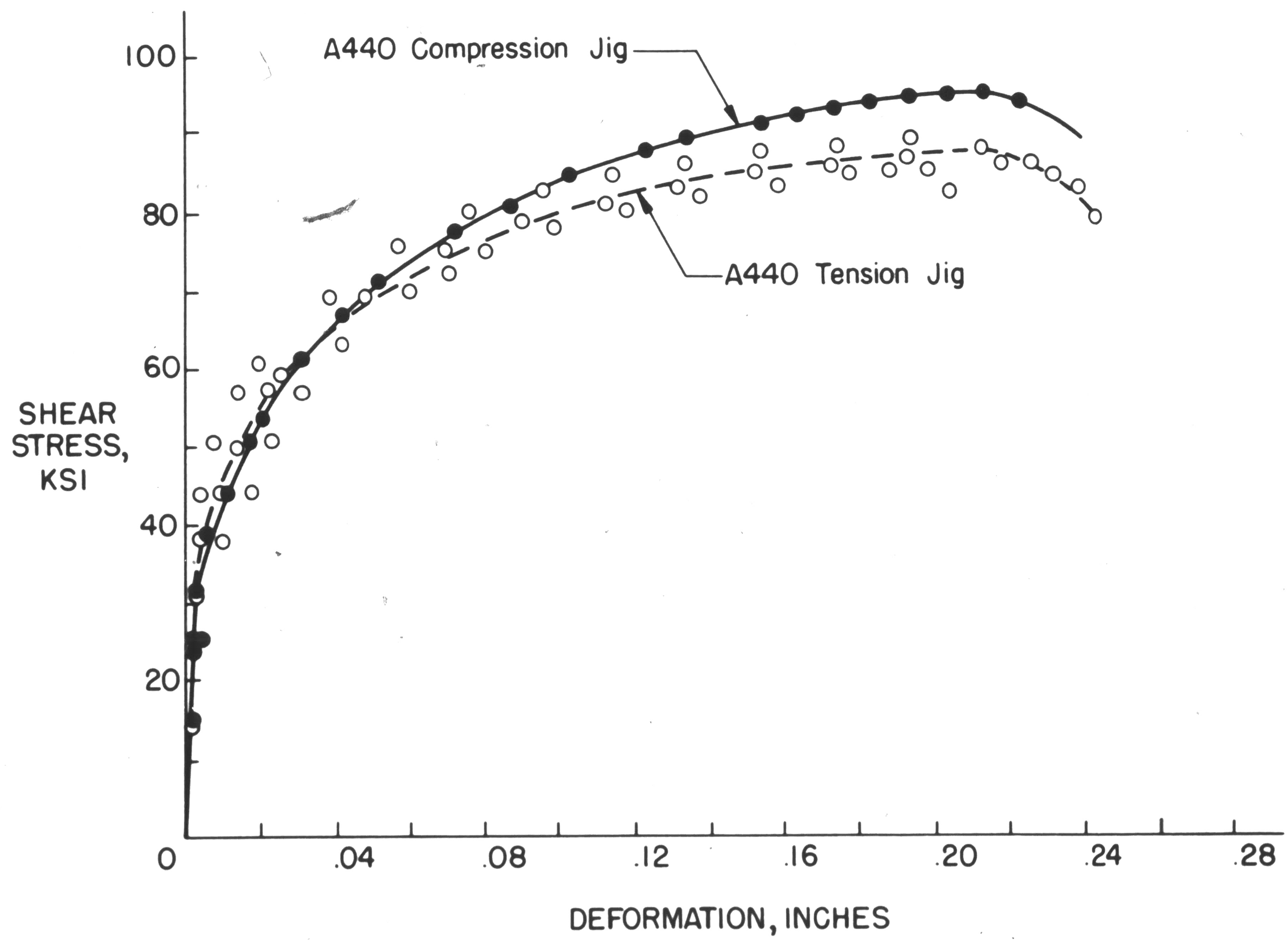



Fig. 10 Typical Stress-Deformation Curves for A354 Bolts Tested in Tension and Compression Jigs

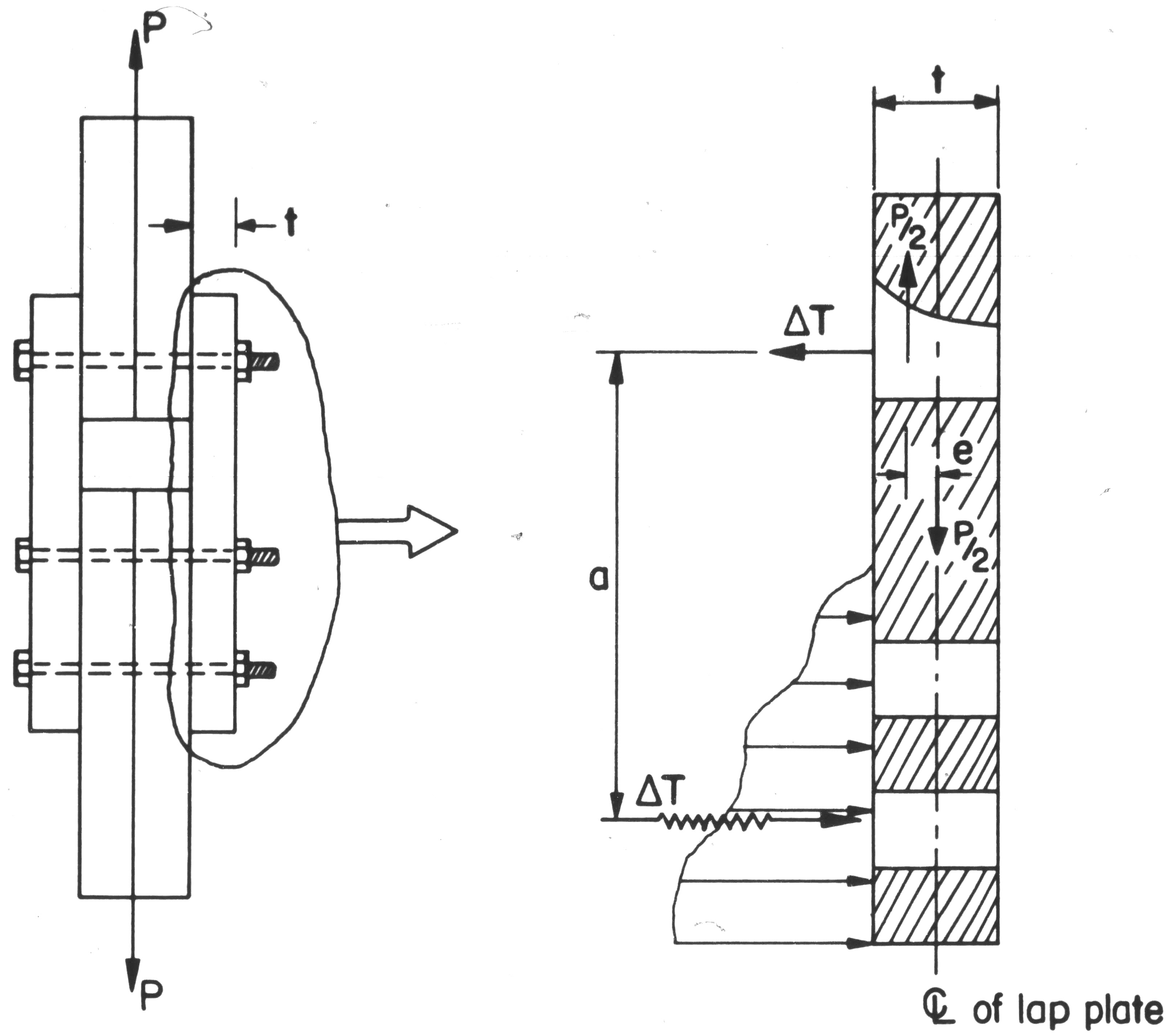



Fig. 11 Lap Plate Prying Mechanism

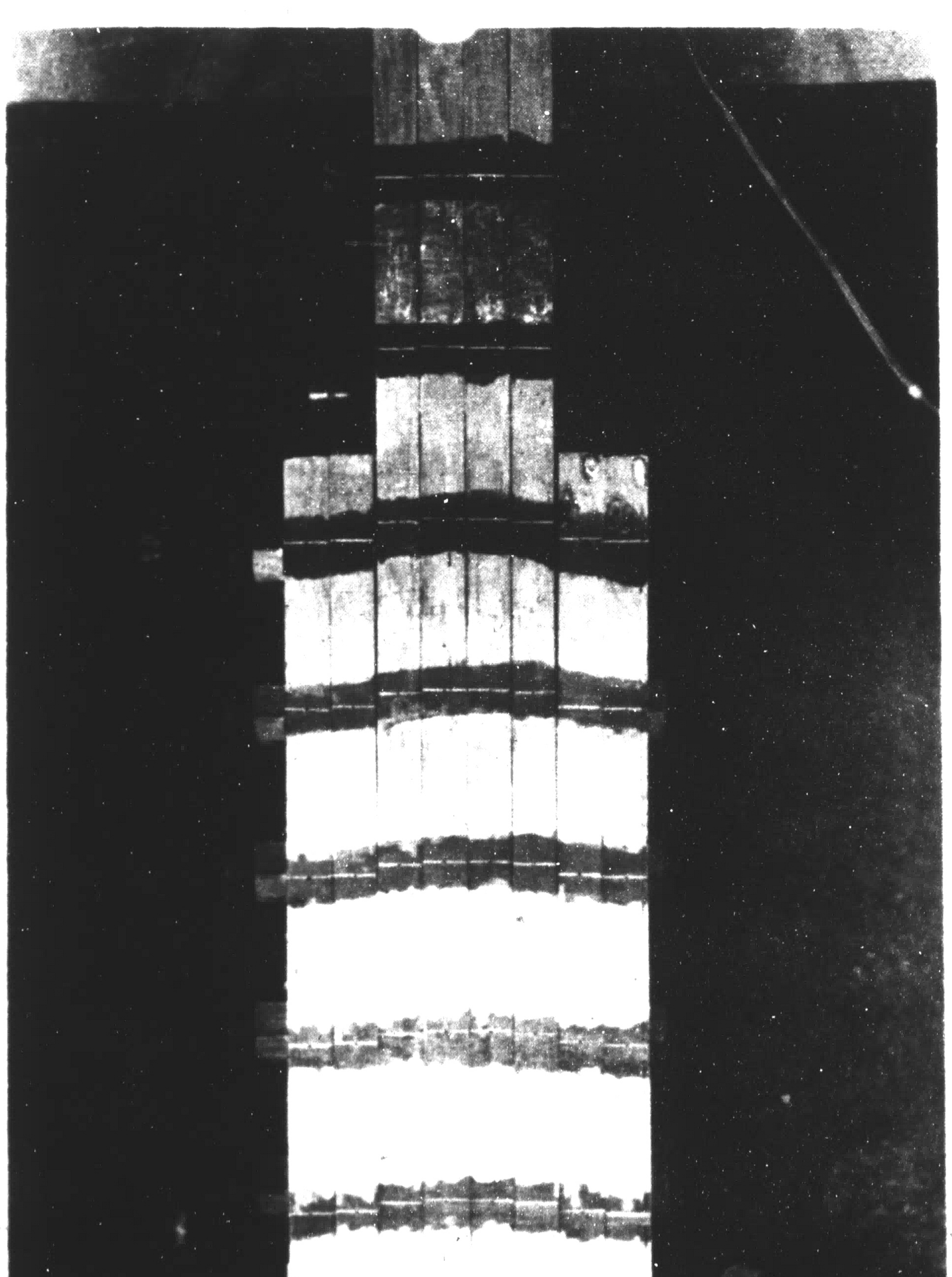


Fig. 12 Illustration of Lap Plate Prying in a Large Bolted Joint

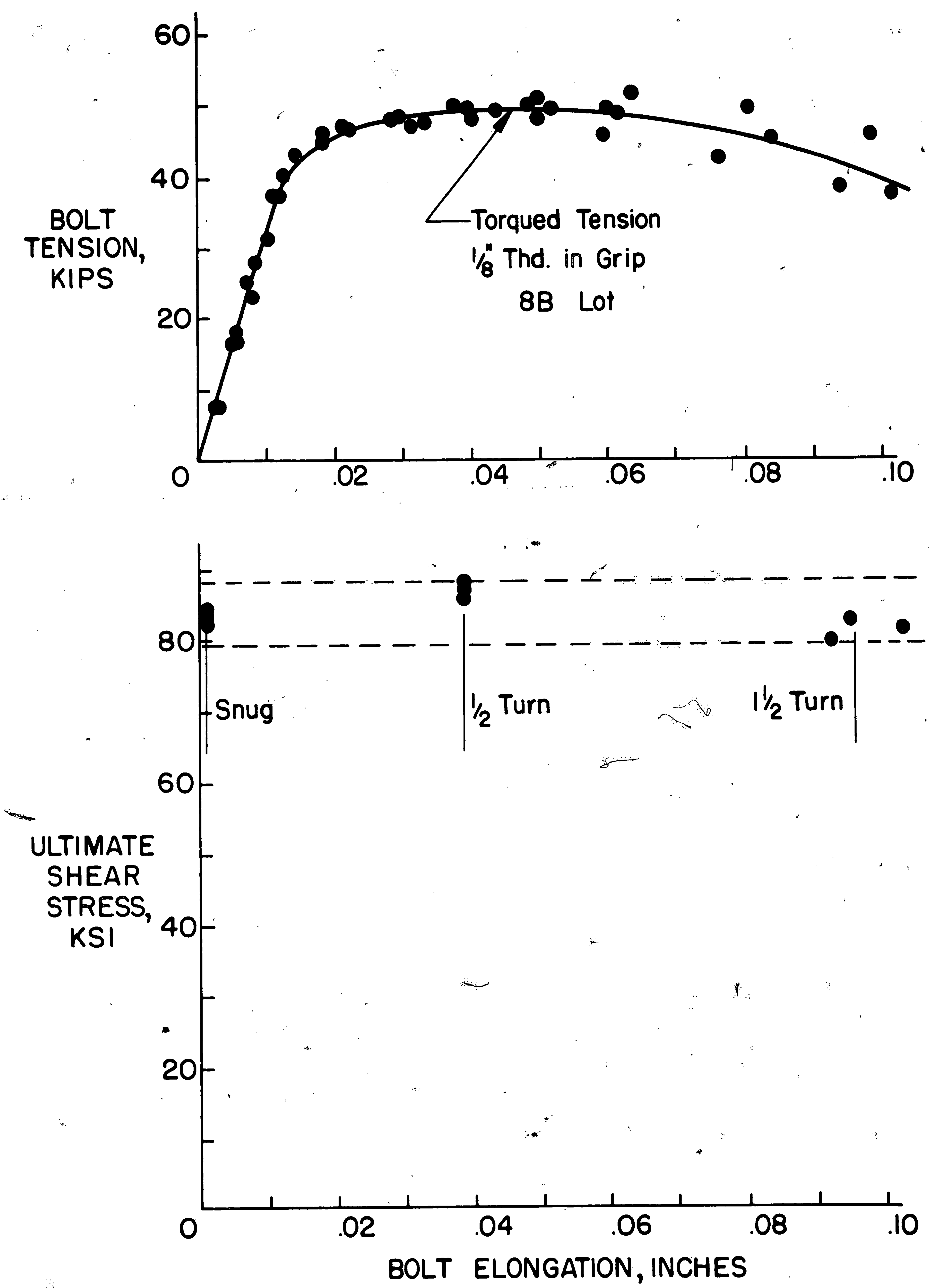



Fig. 13 Effect of Bolt Preload on the Ultimate Shear Strength of A325 Bolts

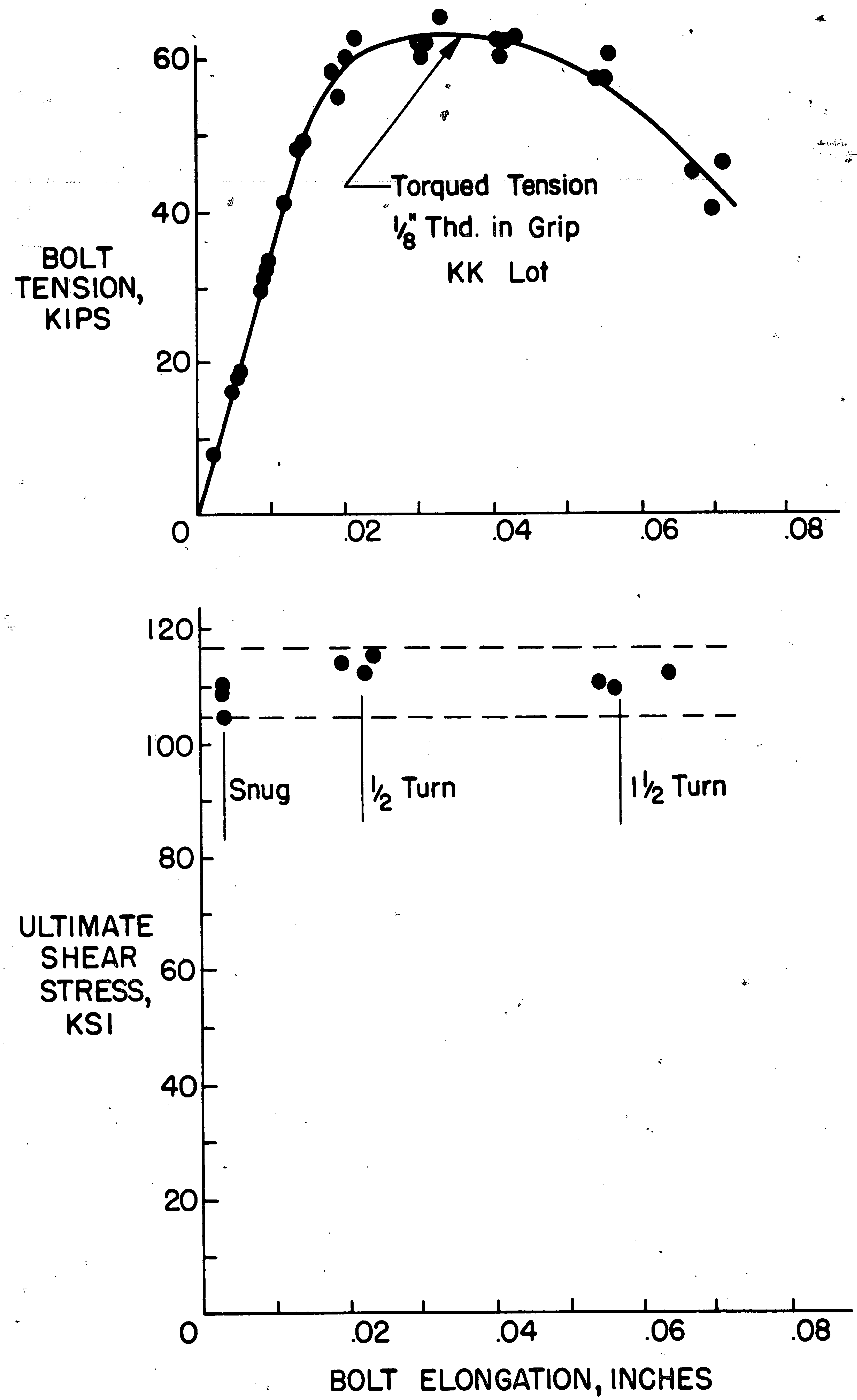



Fig. 14 Effect of Bolt Preload on the Ultimate Shear Strength of A490 Bolts

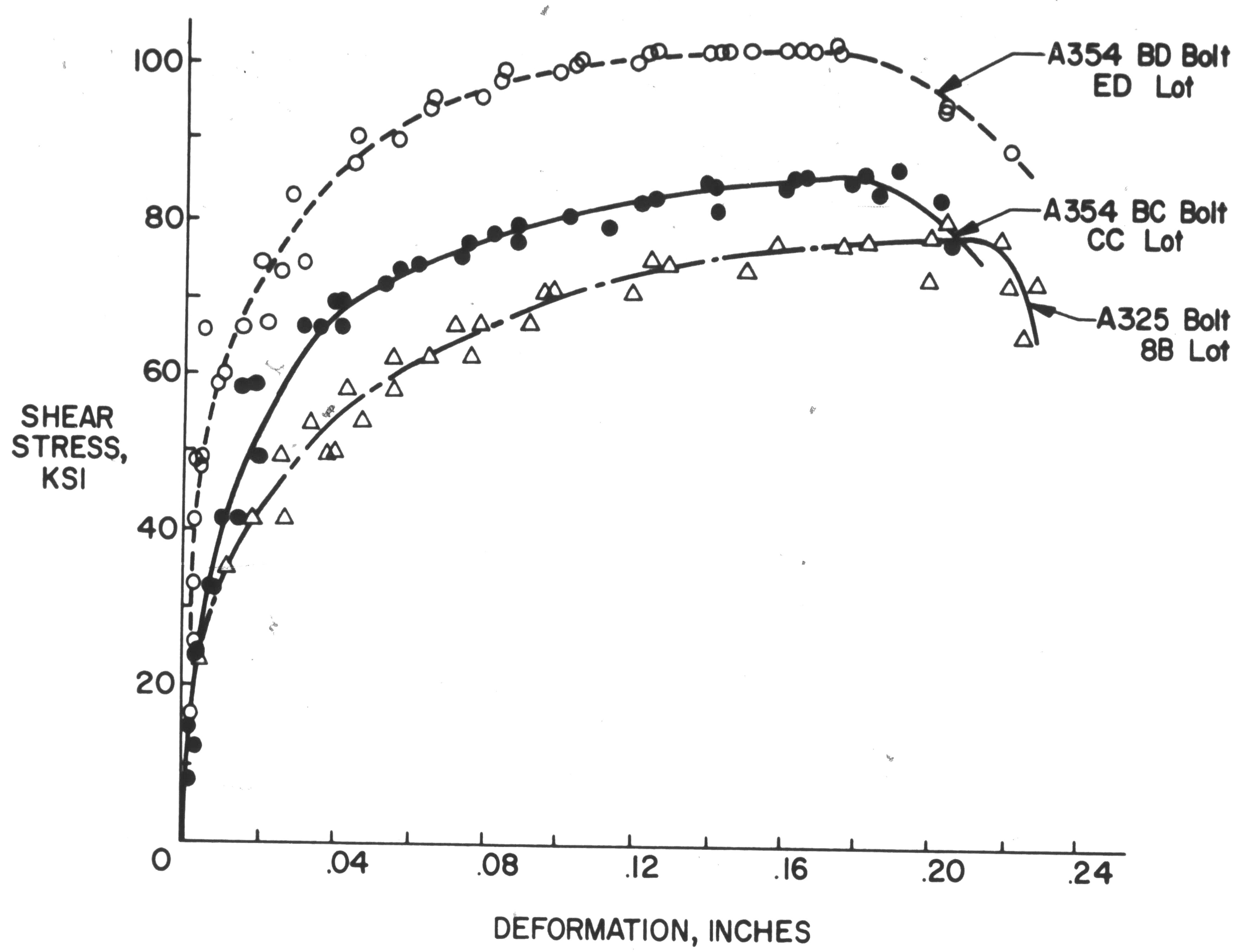



Fig. 15 Typical Stress-Deformation for Bolts Tested in A440 Tension Jigs

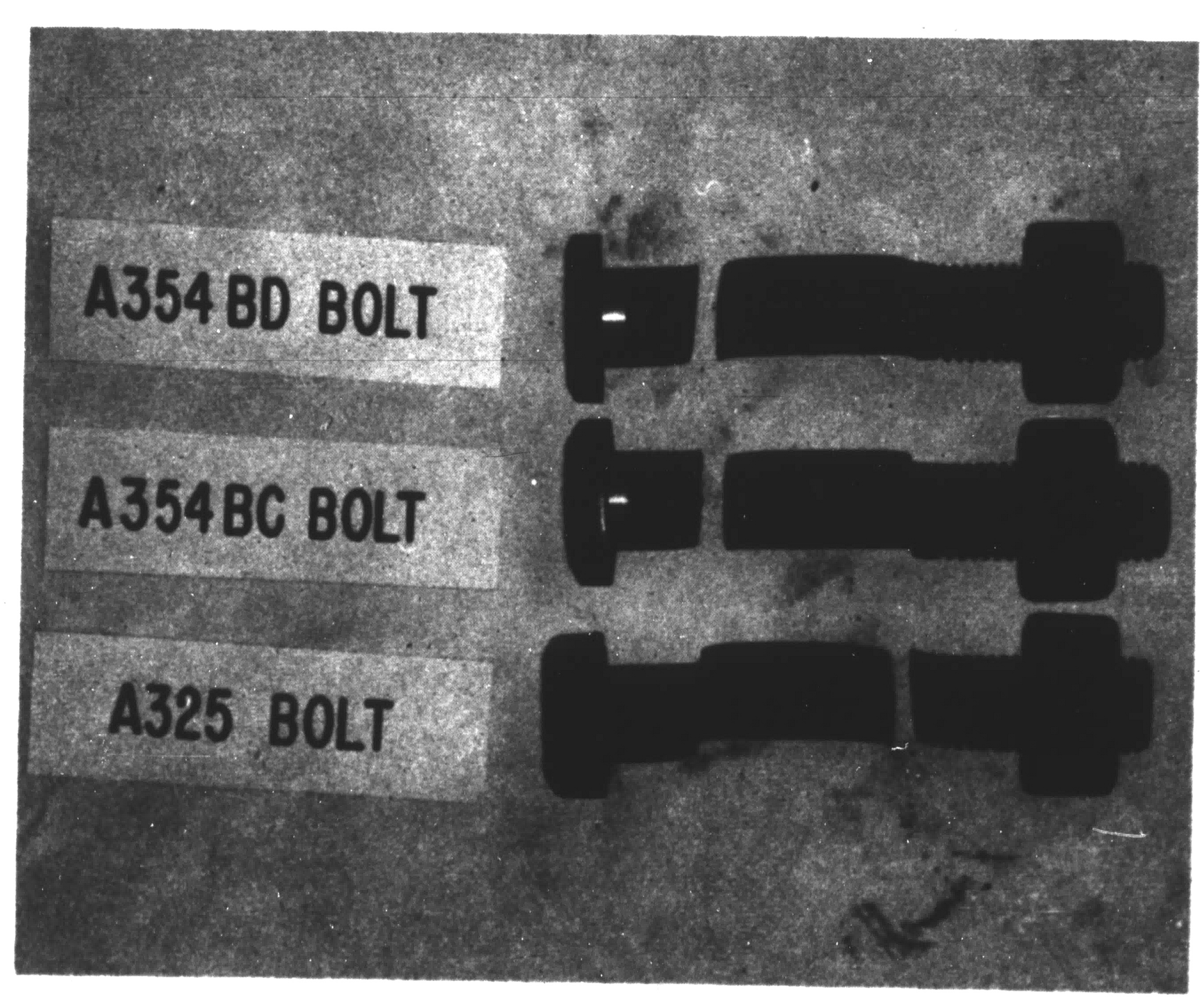



Fig. 16 Bolts Failed in Shear

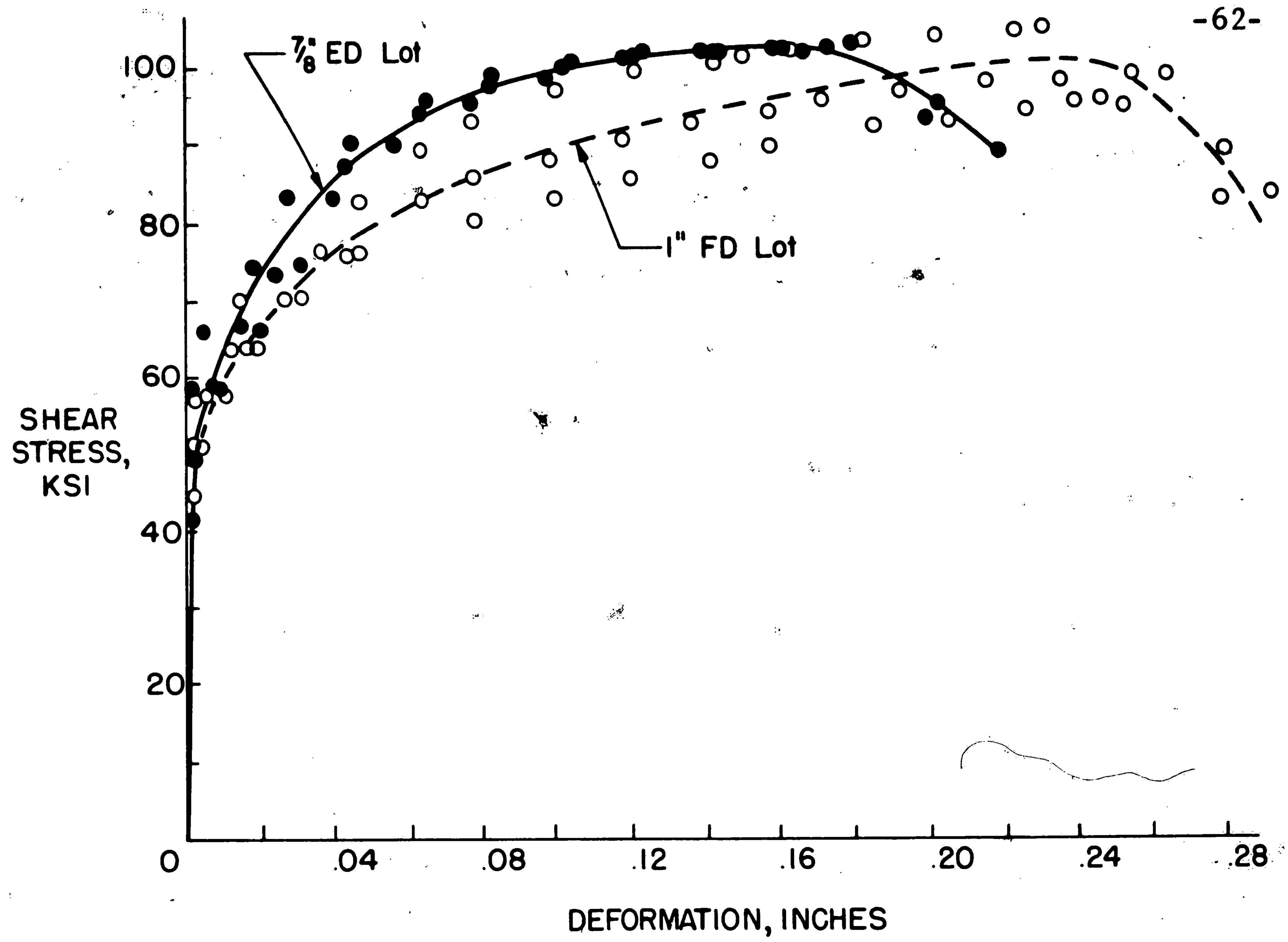



Fig. 17 Typical Stress-Deformation Curves for 7/8" and 1" Bolts Tested in A440 Tension Jigs

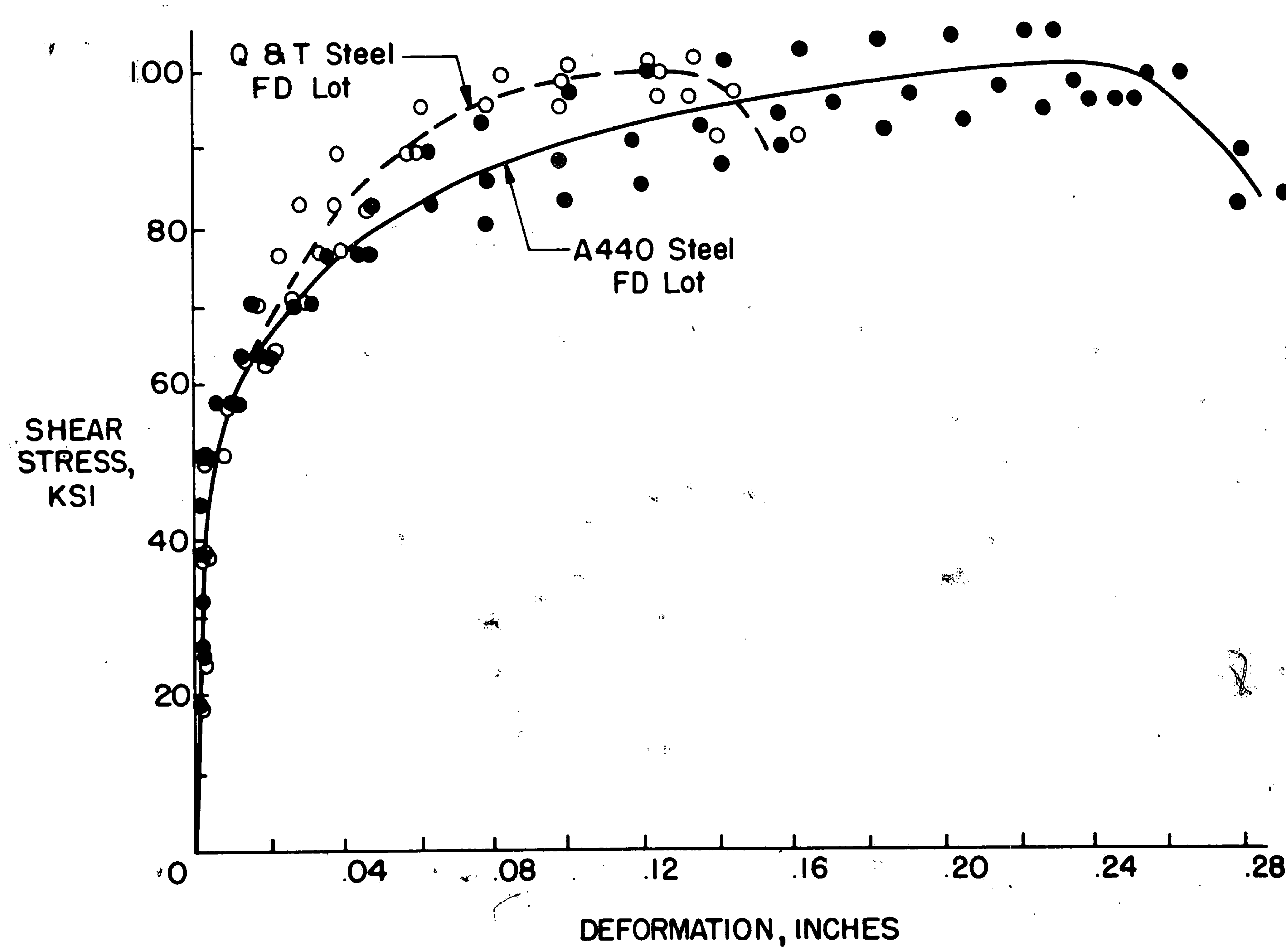



Fig. 18 Typical Stress-Deformation Curves for A354 BD Bolts Tested in Tension Jigs

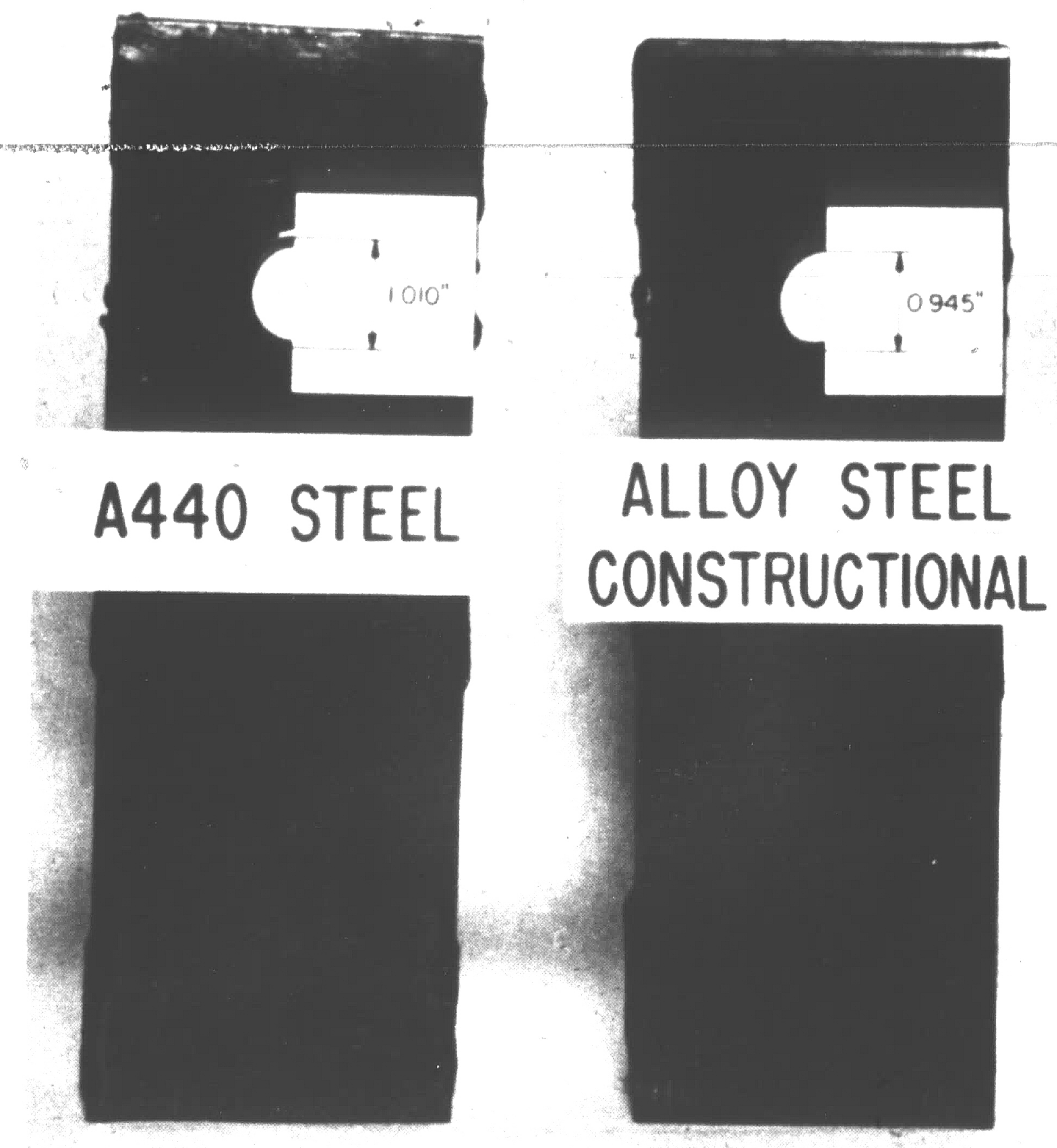
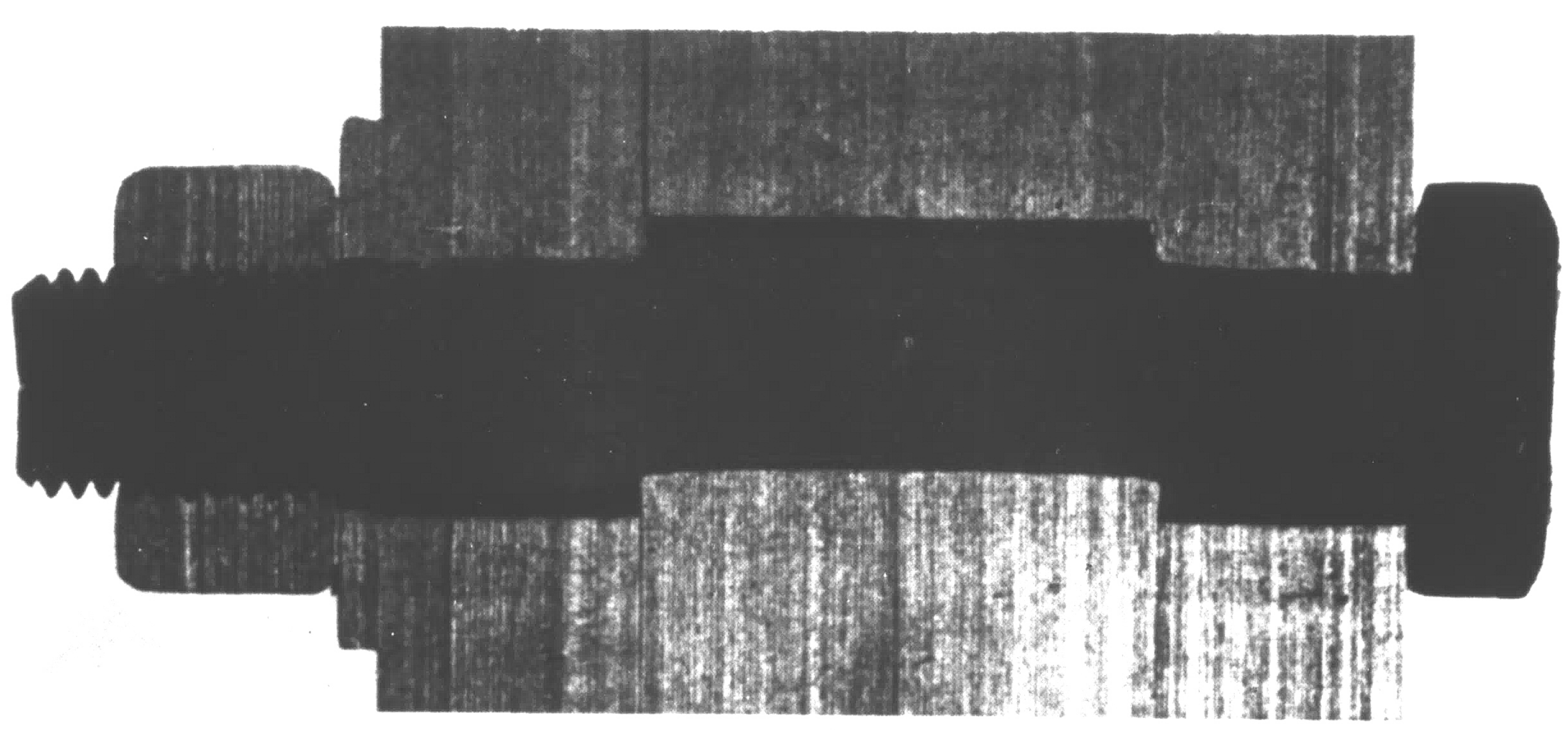
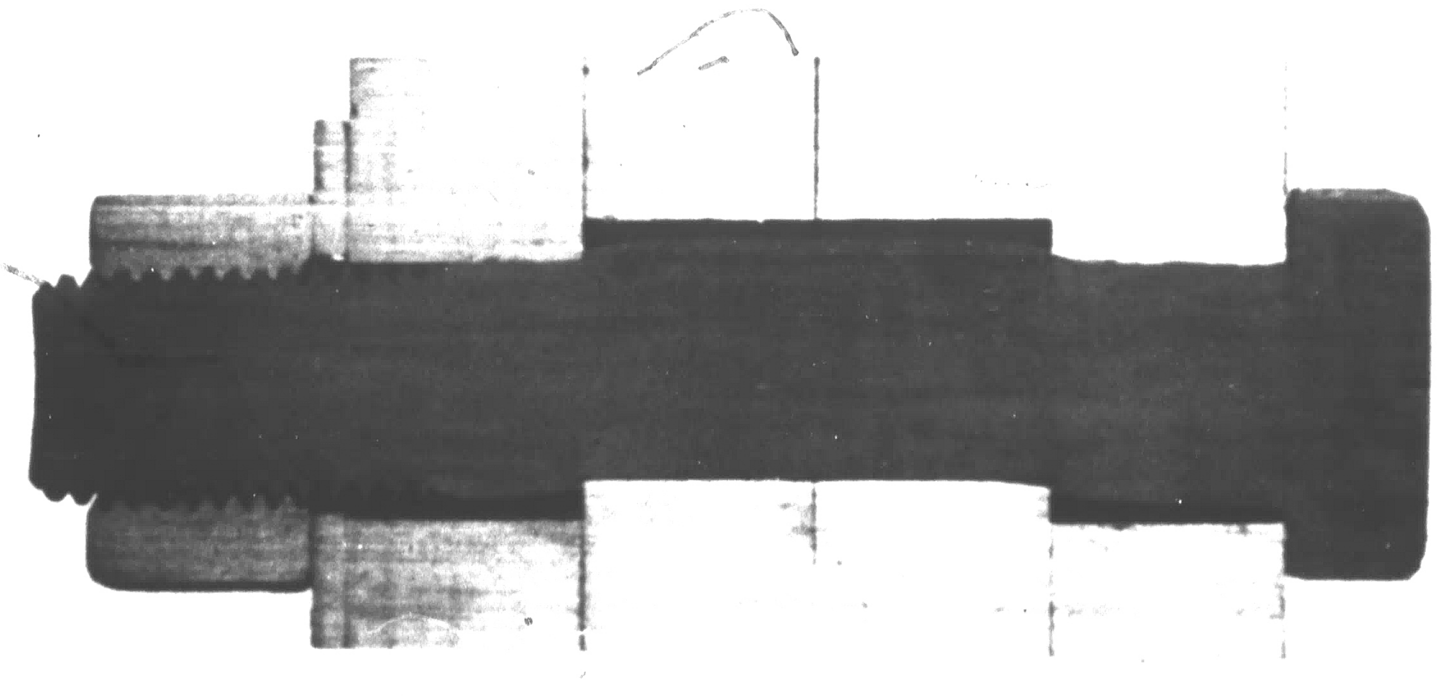



Fig. 19 Hole Bearing Deformations in Different Types of Steel



A325 Bolt
A440 Steel



A490 Bolt
Q & T Steel

Fig. 20 Sawed Sections of A325 Bolts in A440 and Q & T Steel Jigs

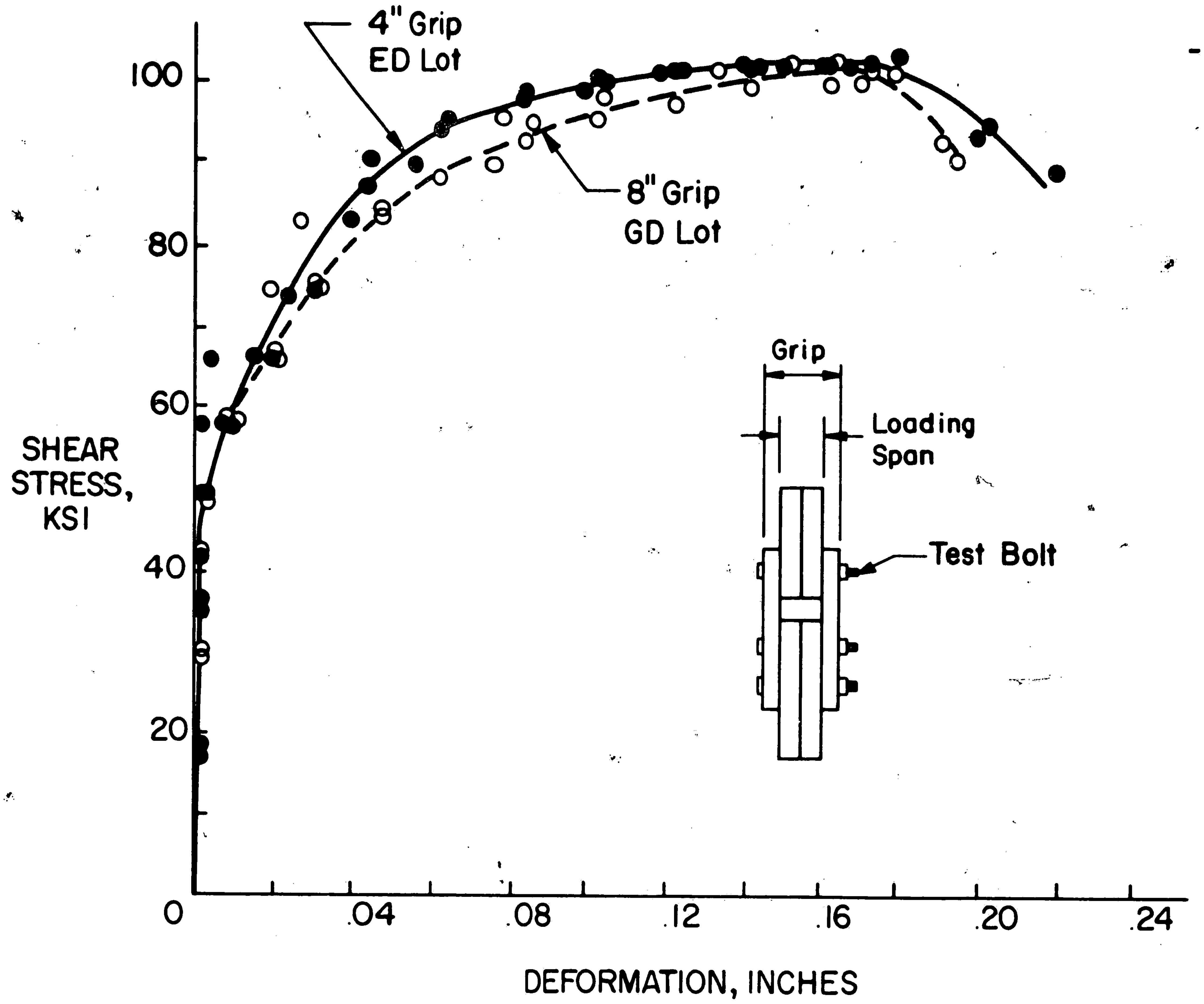



Fig. 21 Effect of Grip and Loading Span

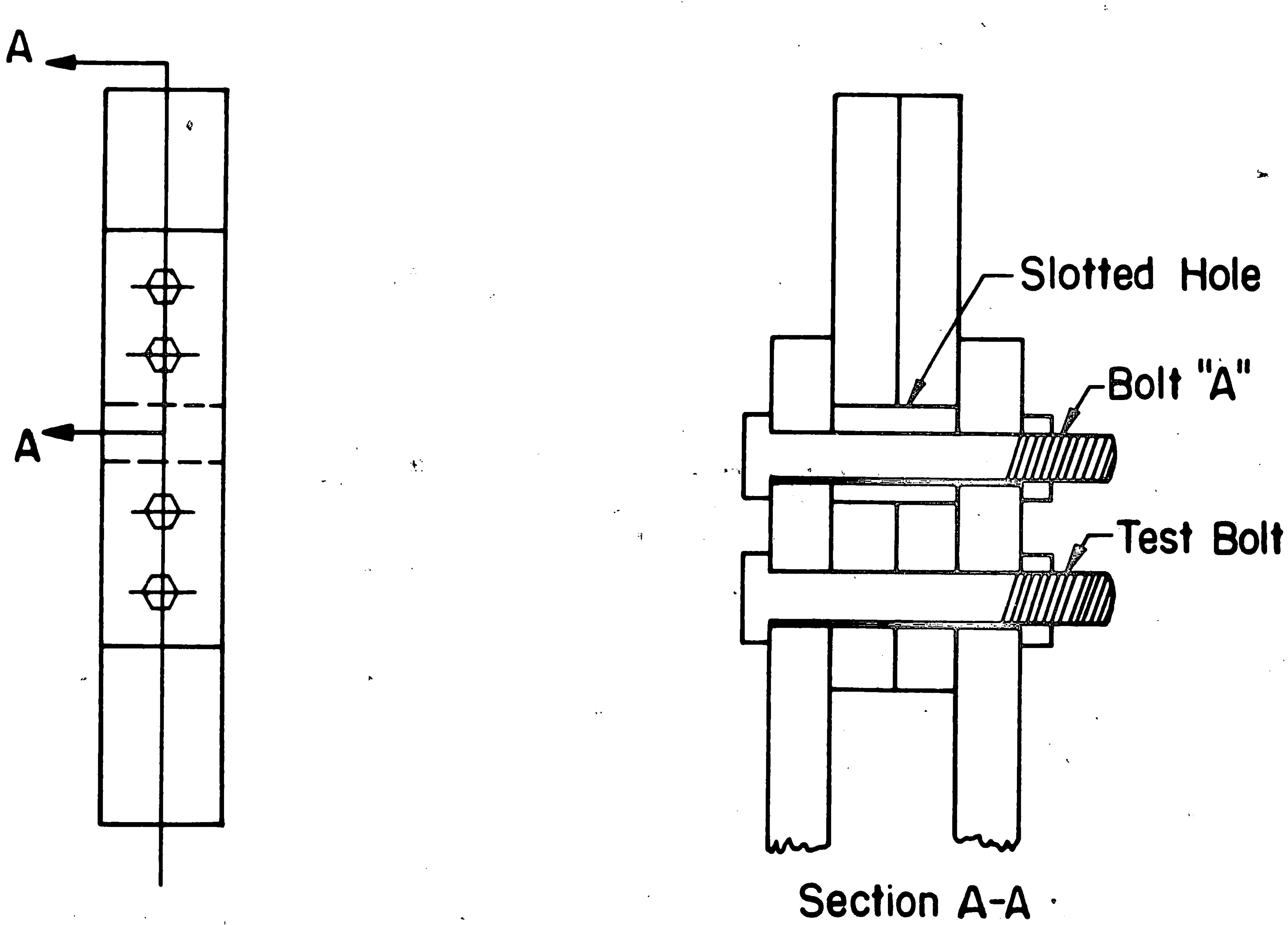



Fig. 22 Special Tension Jig to Eliminate Lap Plate Prying

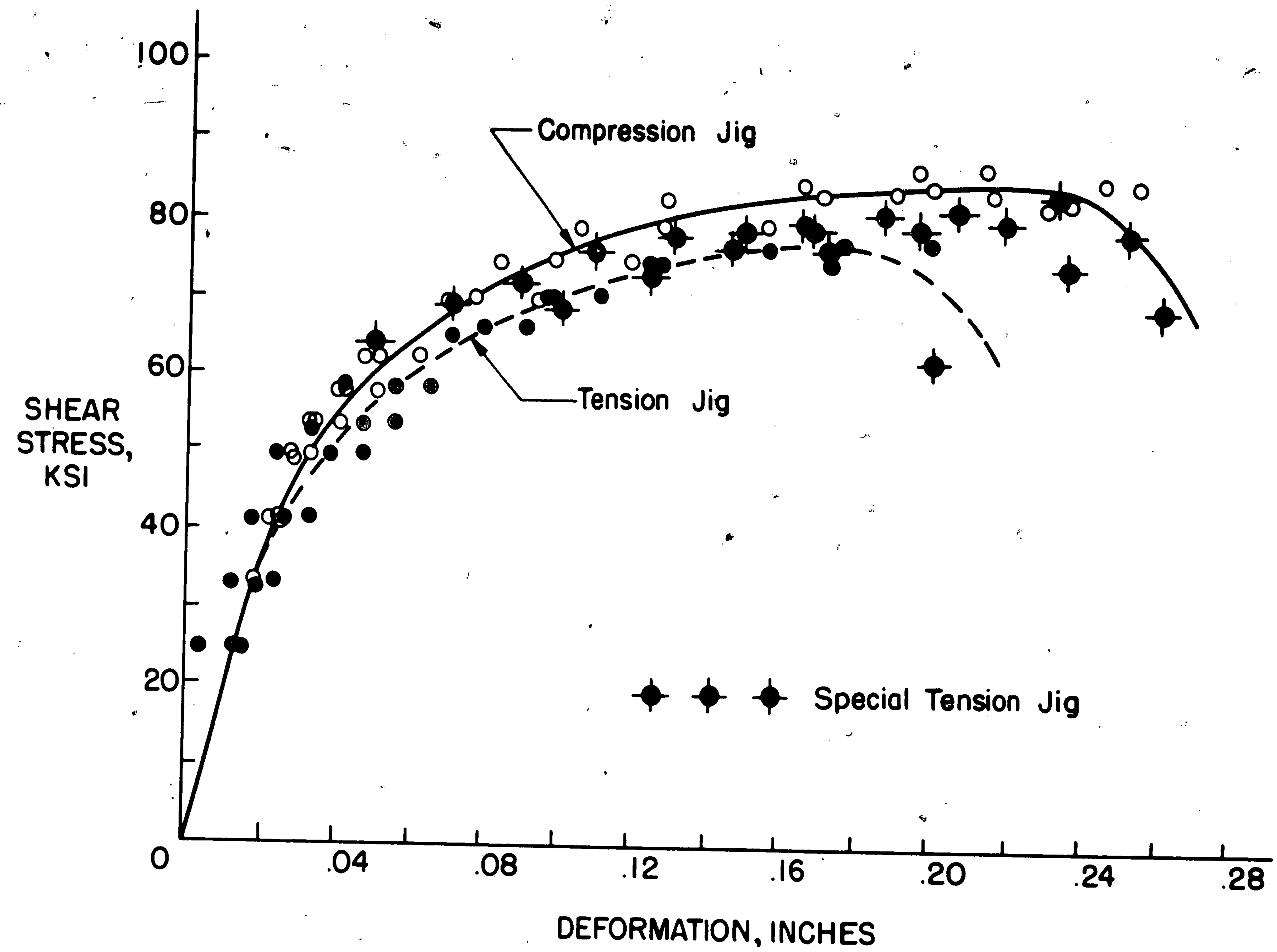



Fig. 23 Influence of End Restraint on the Shear Strength of A325 Bolts

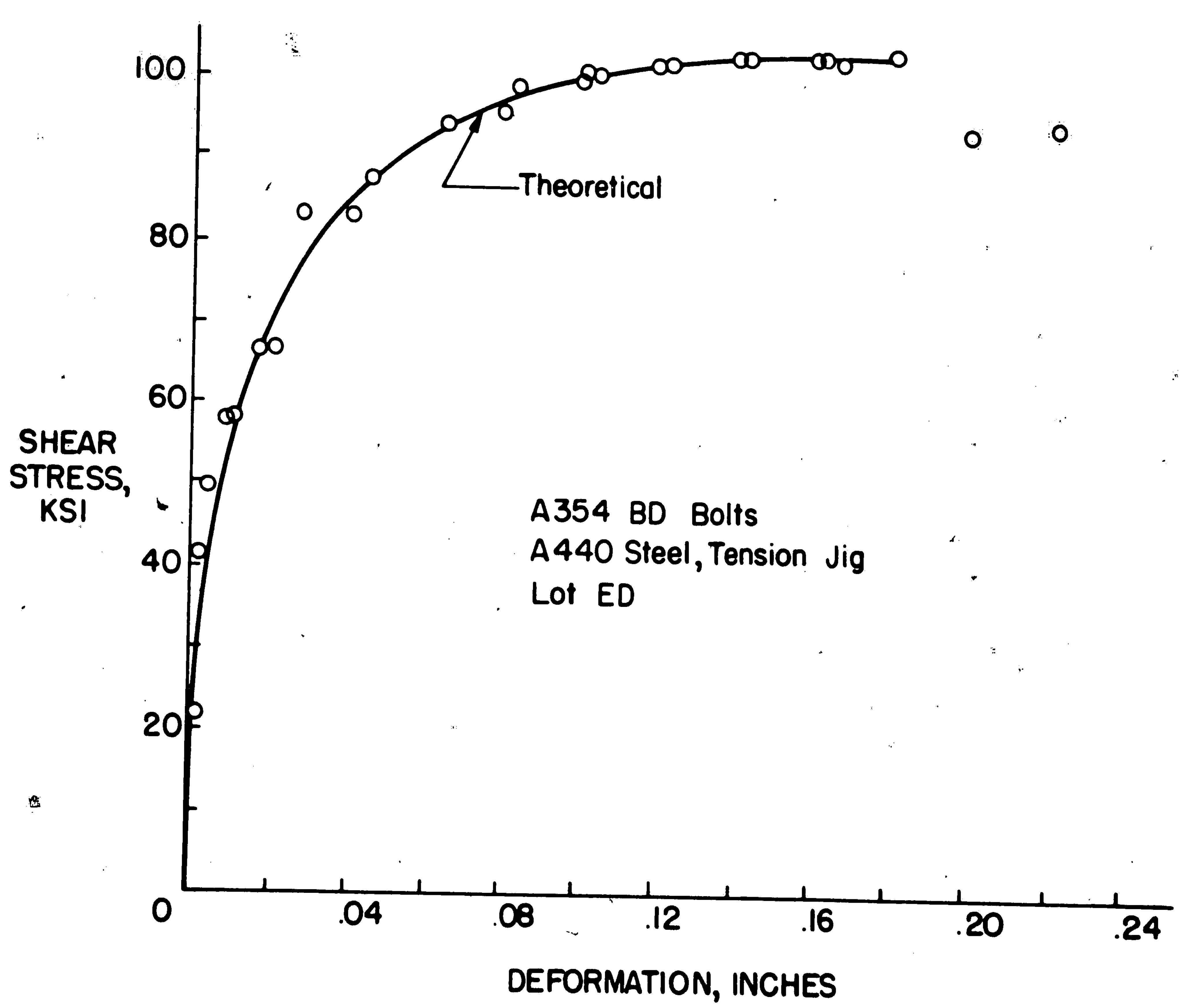



Fig. 24 Stress-Deformation Curves for A354 BD Bolts Tested in A440 Steel Jigs

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